EXPERIMENTAL STUDY OF THE COMPROMISES BETWEEN MECHANICAL PROPERTIES AND LEVEL OF RECYCLED MATERIAL FOR PLASTIC PARTS

CARLOS CASTILLO

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DEDICATION

I would like to dedicate this work to my parents and sister for their understanding, support, and most of all love. They have been my inspiration to set higher goals for myself and the reason of all my efforts. Without the, this work would not have been possible.

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Chapter I
Introduction

Nowadays, many types of industries are turning their attention to the reduction of the amount of wasted raw materials in their manufacturing processes. The common trend aims to reuse this material, recycling it. The same holds true for plastics. The challenge that engineers face is to understand and to control the processability and variations in the physical properties of the plastic material when subjected to a recycling process. Consequently, the process settings in the injection molding process (IM) and the product mechanical properties may be dependent on the extent of recycled material used.

Injection molding (IM) is considered the most prominent processes for mass-producing plastic products. One of the biggest challenges facing manufacturers today is to determine the amount of recycled plastic material they can use to manufacture a new part without suffering a loss in the part's mechanical properties, such as tensile strength (TS), impact resistance, and flexural strength (FS). In addition, selecting the proper settings for an IM process is crucial because the behavior of the polymeric material during shaping is highly influenced by the process variables and influences directly the final mechanical properties of the part. Consequently, the process variables govern the quality of the part produced. The difficulty of optimizing an IM process is that the performance measures -quantities that characterize the adequacy of part and the intended purposes, such as surface quality or cycle time, show conflicting behavior. Therefore, a compromise must be found between all of the performance measures of interest. Furthermore, their values will most likely be influenced by the amount of recycled material used.

In today's world virtually every manufactured good can technically be recycled in some form, and in addition, goods' manufacturers are trying to improve the recyclability of their products, hence reducing the scrap and material disposed [1]. Whether motivated by recent legislative efforts or by moral sense of obligation, the reutilization of material reduces the environmental impact generated by wasted material and generates economic savings. For example, automotive manufacturers are interested in recycling their scrap, which is an inevitable product of the manufacturing process, in order to use it in combination with virgin material as raw material for new parts, such as bumpers or instrument panels. The material analyzed in this research is a thermoplastic polyolefin (TPO).

In principle, the recycled material can be combined with the virgin material and injected together to manufacture a new part. The effect on the mechanical properties of the part correlates with the percentage of recycled material added. However, when the plastic material has been coated -painted, for example-, an individual analysis has to be carried on since paint chips greatly affect the final mechanical properties of the injected part. Not only the overall strength of the material is affected but also there is a negative effect on the surface quality. In the case of a painted part –a bumper or an instrument panel-, the most likely best solution is to use it as the core material in a co-injection molding process. This advanced injection molding process is not widely used yet, which results on a great amount of painted plastic parts that do not satisfy the quality requirements to be discarded as waste or land-filled with the consequent ecological impact. Co-injection molding will be briefly introduced and discussed in this work; however, due to a delay in the availability of a co-injection machine, research on the mechanical properties of co-injected parts made of TPO was not possible.

In summary, this work will investigate the largest amount of unpainted bumper scrap that can be added to virgin material and still meet the Honda engineering specifications. For that, mechanical properties of experimental mixes will be evaluated for strength under static conditions. The purpose of these tests for the unpainted material is to define the maximum percentage that can be used without affecting the mechanical properties of the part. In contrast, in the case of the painted material the tests are run to determine the feasibility of using it as a structural component of a co-injected part.

CHAPTER II
Co-Injection

Co-injection molding (CIM) is an innovative manufacturing method that could serve to use grinded painted recycled bumper material as part of a new piece. There are two main types of co-injection molding. The first is referred to as two color molding. In two-color molding a part is molded using one resin, and then a second resin is molded into the first once the former has been sufficiently cooled and after the mold retracted or the part rotated to a second larger cavity. This technology is used in products such as computer keys and multi-colored automotive taillights [2]. The second, and more common, type of co-injection molding involves the injection of a skin material and a core material. This is also known as "sandwich molding" because the core material is sandwiched in between the skin material. Sandwich molding is a variation of injection molding in which two different plastics are either simultaneously or in rapid sequence injected through the same gate [3]. The inner material makes up the core of the product and the outer one makes up the skin. Through the combination of two different materials several benefits can be obtained that traditional injection molding can not supply by itself. This second approach, which is sandwich molding, is the one that is being considered for the big automotive parts. The core material will be the regrind painted material and the skin will be of virgin material [Figure 2.1]

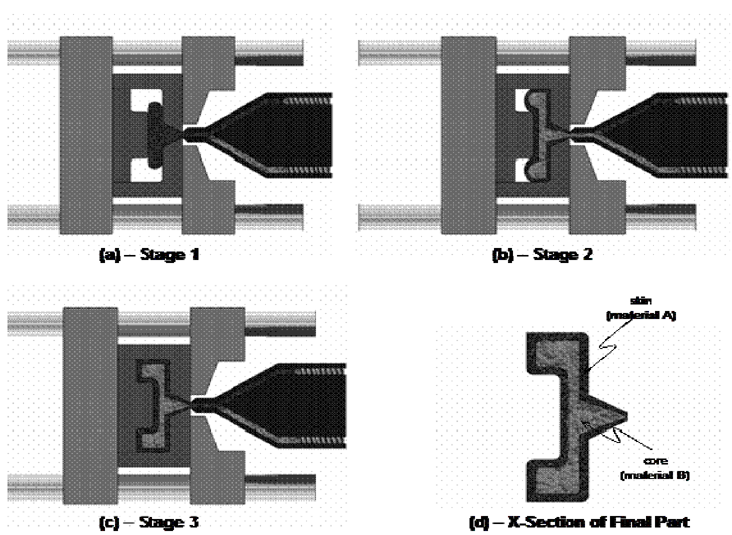


Figure 2.1: Sandwich molding machine with a common nozzle and switching head [14]

A further attractive idea is to use microcellular foam in the core material to decrease the total weight of the part. The Center of Advanced Polymers and Composite Engineering (CAPCE) with help of the Honda/OSU partnership has acquired a multi-component injection unit with micro cellular foaming capability that unfortunately was not available for the last part of this research.

Chapter III
The Recycling Problem of Honda

Honda as one of North America's largest automotive manufacturers is interested in increasing the use of recycled material in all their operations. Honda's manufacturing processes, such as injection molding of bumpers and thermoforming of instrument panels, generate scrap. This thesis focuses on the study and analysis of the material used in the Honda Accord bumper which is a polyolefin. More specifically, Sequel 1490 is an engineered thermoplastic polyolefin material designed for automotive exterior applications that require a combination of stiffness, low temperature impact resistance, and excellent processability [7].

There are two types of regrind material that will be studied. The firs type is *unpainted regrind* that is result of grinding defective bumpers that have not yet been coated with paint. The second type is *painted regrind* which is the product of grinding of bumpers that were found defective after they went through the painting process. The difference between these two types of materials is critical since while the former material is being reused up to a 20% as a constituent of new parts, the latter is entirely discarded in the form of land filling with the consequent ecological impact. The reason for Honda to not use the painted regrind is based on the poor surface quality that it yields for a new part.

This work will evaluate the alternative to increase the percentage of unpainted regrind material used in new manufactured parts. In addition, the painted regrind will also be analyzed similarly to its unpainted counterpart, however, as it will be shown, the painted material will not be used as a component of a mix but rather as the core of a co-injected part

The constraints imposed by the problem itself result from Honda's Engineering specifications that take into account preferred manufacturing procedures and safety issues which are critical in parts such as the bumper that is studied. There are five main material properties that will be the object of this study and will serve as performance measures for the different material mixes to be analyzed; they are: Impact Strength, Tensile Strength, Tensile Elongation at Break, Flexural Strength, and Flexural Modulus.

Table 3.1 shows each of the mentioned properties along with its Honda Engineering Specification and Honda’s typical values which will be used as performance measure.

Property		Units (SI)	Specification	Honda Typical Values
Impact Strength	23 C	J/m	No Break	No Break
	- 30 C		>59	70
Tensile Strength		MPa	>15.7	16.5
Tensile Elongation at Break		%	>200	425
Flexural Strength		MPa	>17.6	28
Flexural Modulus			>1470	1490

Table 3.1 Honda Engineering Specifications for five main material properties

Currently, Honda is using 20% of their recycled unpainted regrind material; however, the company is interested in evaluating what is the largest quantity of this type of regrind that they can use in a new part without falling below their own specifications.

Chapter IV
Technical Background

4.1 Injection Molding

IM is considered the most important manufacturing process for mass producing plastic parts. Molten plastic is injected at high pressure into a mold. The mold is made by a moldmaker (or toolmaker) from metal, usually either steel or aluminum, and precision-machining is used to form the features of the desired part. Over one half of all polymer-processing equipment is used for injection molding, and over a third of all thermoplastic parts are manufactured by IM [1]. Injection molding is very widely used for manufacturing a variety of parts, from the smallest component to entire body panels of cars. The most common type of injection molding machine is called a reciprocating screw machine. A schematic of a typical injection molding machine is shown in Figure 4.1. It is the most common method of production, with some commonly made items including bottle caps and outdoor furniture.

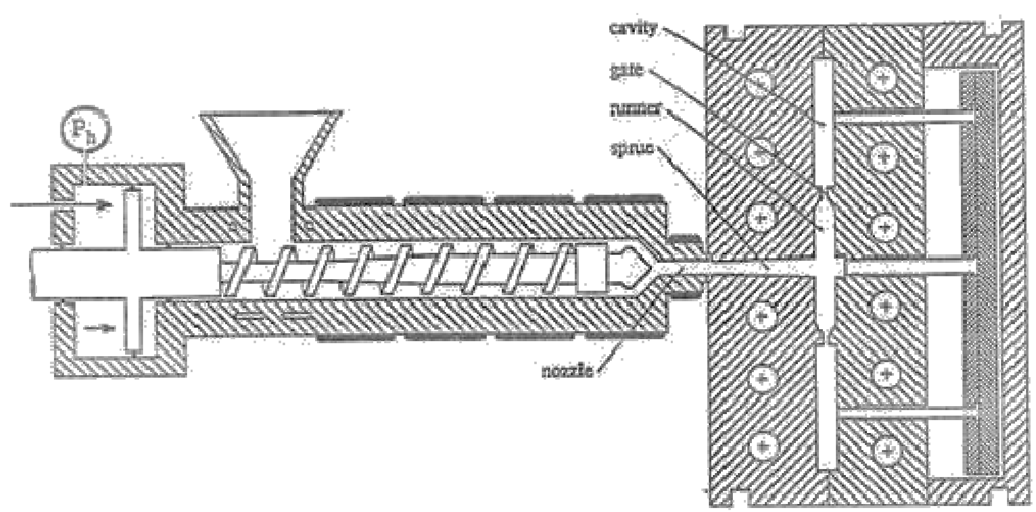


Figure 4.1 Typical reciprocating screw injection molding machine

4.2 Mold Filling Process

The injection molding process occurs cyclically. Typical cycle times range from 10 to 100 seconds and are controlled by the cooling time of the thermoplastic or the curing time of the thermosetting plastic. Before the actual injection molding cycle begins, the material is fed into the hopper, a large open bottomed container, in the form of pellets. Heaters on either side of the screw assist in the heating and temperature control around the pellets during the melting process. Due to the shear heating and the heaters, the pellets are melted. The injection molding cycle begins with the screw turning in order to accumulate the plastic at the front of the barrel. The screw is turned by a hydraulic or electric motor that turns the screw feeding the pellets up the screw's grooves. The depths of the screw flights decrease towards the end of the screw nearest the mold. As the plastic is accumulating at the front of the barrel, the screw is forced backwards. The screw travel limit switches set the distance the screw moves. When the proper amount of plastic is accumulated, the screw plunges forward and injects the plastic into the mold cavity. After the cavity is filled, the machine increases the pressure to the holding pressure. Once the material cools to the defined ejection temperature, the mold opens, and the part is ejected. The cycle is then repeated.

A graph of the pressure at the point of injection is shown in Figure 4.2. The screw rotates forward and fills the mold with melt. During the injection of the plastic, the pressure increases. Once the plastic is injected, the screw holds the melt under high pressure, and ads more melt to compensate for the contraction due to cooling and solidification of the polymer. This is called the hold time. The holding phase ends either when the gate freezes (cold runner) or by closing a valve when the user desires (hot runner). Next the screw begins to rotate and more melt is generated for the next shot. In the soak time the screw is stationary and the polymer melts by heat conduction from the barrel to the polymer. The solidified part is then ejected and the mold closes for the next shot.

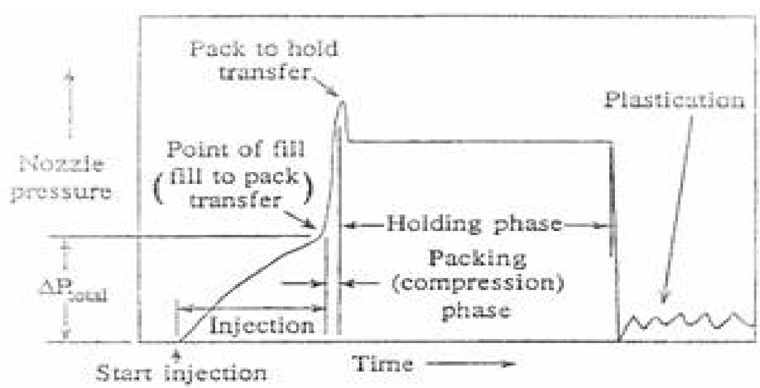


Figure 4.2 Pressure at the injection location for one cycle of injection molding [4]

4.3 The Mold

Considerable thought is put into the design of molded parts and their molds, to ensure that the parts will not be trapped in the mold, that the molds can be completely filled before the molten resin solidifies, to compensate for material shrinkage, and to minimize imperfections in the parts –i.e. flash and warpage- which can occur due to peculiarities of the process.

Molds separate into at least two halves (called the *core* and the *cavity*) to permit the part to be extracted; in general the shape of a part must be such that it will not be locked into the mold. Parts shrink onto the core while cooling and, after the cavity is pulled away, are typically ejected using pins. A diagram of all the constituent parts of a typical mold are shown in Figure 4.3

The raw material for injection molding, is usually in pellet form, and is melted by heat and shearing forces shortly before being injected into the mold. The channels through which the plastic flows toward the chamber will also solidify, forming an attached frame. This frame is composed of the *sprue*, which is the main channel from the nozzle, parallel with the direction of draw, and *runners*, which are perpendicular to the direction of draw, and are used to convey molten plastic to the *gate(s)*, or point(s) of injection. The sprue and runner system can be cut off and recycled.

The quality of the molded part depends on the quality of the mold, the care taken during the molding process, and upon details of the design of the part itself. It is essential that the molten resin be at just the right pressure and temperature, so that it flows easily to all parts of the mold. The parts of the mold must also come together extremely precisely, otherwise small leakages of molten plastic can form, a phenomenon known as *flash*. When filling a mold with a new material for the first time, where injecting speed and shot size for that particular mold are unknown, a technician should reduce the nozzle pressure so that the mold fills, but does not flash. Then, using that now-known shot volume, pressure can be raised without fear of damaging the mold. Sometimes factors such as temperature, and resin moisture content, can effect the formation of flash as well.

The hydraulic system pumps oil from the oil tank to firmly close the male and female mold parts, which run along the tie bar; the liquid resin is then injected into the mold.

Since the molds are clamped shut by the hydraulics, the heated plastic is forced under the pressure of the injection screw to take the shape of the mold. The water-cooling channels then assist in cooling the mold and the heated plastic solidifies into the part. The cycle is completed when the mold opens and the part is ejected (with the assistance of ejector pins within the mold).

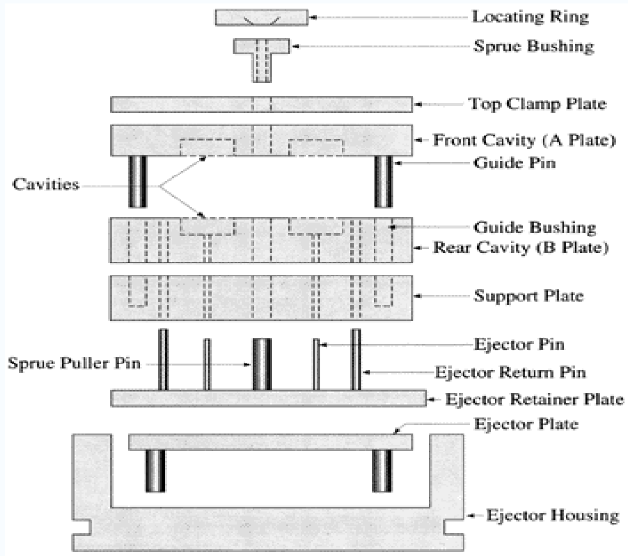


Figure 4.3 Schematic view of a typical IM mold [13]

4.4 ASTM Standards

The American Society for Testing Materials (ASTM) is an organization to establish test standards for materials, products, systems, and services for a wide range of industries. ASTM formulates test methods and material specifications, and publishes standards, testing methods, recommended practices, definitions, and other materials. ASTM's committee on plastics has published three standards under which the values in the Specification column of Figure 2 were obtained; ASTM D 256, ASTM D 638, and ASTM D 790.

ASTM D 256 is the Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics that will be used to determine the Impact Strength of the experimental notched specimens. ASTM D 638 is the Standard Test Method for Tensile Property of Plastics that will be used to determine Tensile Strength and Tensile Elongation at Break of "dog bone" specimens. ASTM D 790 is the Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Material which will be used to determine the Flexural Strength and Flexural Modulus.

CHAPTER V
Experimental

5.1 Material

A polyolefin is a synthetic plastic group the plastic forming substance is any long-chain synthetic polymer composed of least 85% by weight of ethylene, propylene, or other olefin units. Polyethylene and polypropylene represent this group [9]. In addition, the word thermoplastic refers to those polymeric materials that softens when heated and becomes firm when cooled. The main characteristic of a thermoplastic is that it can be re-melted a number of times without any important changes in its properties [10]. It is this quality of the TPO to be used experimentally that allows the manufacturer to include material from a previously injected bumper into a new mix in which it will be re-melted in order to be injected as a constituent of a new part.

The virgin material to be used experimentally is a thermoplastic polyolefin (TPO) manufactured by Solvay Plastics and provided by Honda under the commercial name of Sequel 1490. The unpainted and painted regrind materials are direct derivations of the virgin TPO after the recycling process that consists on grinding of defective bumpers. Again, the benefits of this material include stiffness, low temperature impact resistance, and excellent processability that appeal to the automotive industry for exterior applications.

5.2 Apparatus

5.2.1 ASTM Mold

The mold used to produce all the specimens used in this work is a hardened steel mold with a 62% yield. The specimens generated are two “dog bone” specimens of Type I as described in ASTM D 638; two long bars with dimensions 125 x 12.7 x 3.2 mm (5 x 1/2 x 1/8 in) in length, width, and thickness respectively; and two discs of different thicknesses that were not used for this thesis. Figure 5.1 shows the typical ASTM specimens that were used in the experimental part of this research

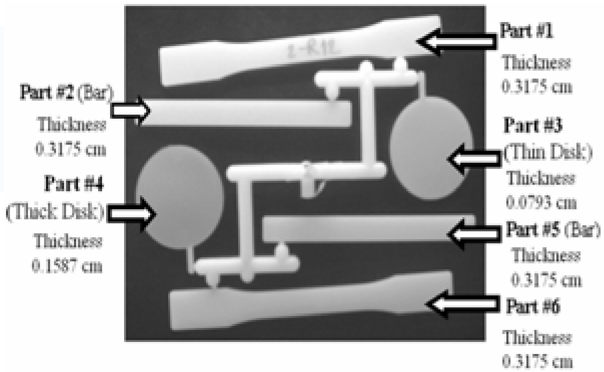


Figure 5.1: Typical injected specimens of an ASTM mold

5.2.2 Injection Molding Machine

A 50-ton Sumitomo Injection [Figure 5.2] molding machine was used to inject the different mixes of TPO to create the specimens. For the sake of consistency, all the specimens of all the mixes were created under the same conditions and with the same machine parameters which are shown in Table 5.1

Temperatures:	425-435-425-400°F	Back Pressure:	3%
Velocity:	83.2 mm/s	Position:	0.80
Packing Pressure:	26.24 MPa	V-P Change:	0.80 -1.00
Packing time:	33 sec	Screw position:	4.1 in
Revolution:	30%		

Table 5.1 Injection Molding Machine Parameters

Figure 5.2. 50-ton Sumitomo Injection Molding Machine

5.2.3 Universal Testing Machine

A Universal Testing Machine (UTM) was employed to perform the tests described in ASTM D 638 and ASTM D 790 in order to obtain the experimental values for all the main mechanical properties of the material, except Impact Strength.

The UTM used for this thesis is an Instron model 5569 Table Mounted Materials Testing System shown in Figure 5.3 with a capacity of 50 kN with digital crosshead speed control. The system includes a 50 kN load cell, a 2-inch extensometer with 100% extension capacity and two 50 kN wedge action grips that were used to obtain the values of the specimen’s mechanical properties following ASTM D 638. In addition, the system consists of a 5 kN compression cell to be used along with a 5 kN 3-Point Bend Flexure Fixture when following the ASTM D 790 method.

Figure 5.3. Instron 5569 Material Testing System

5.2.4 IZOD Impact Tester

In this work an IZOD impact tester with horizontal analogous scale and interchangeable hammer arms was used [Figure 5.4]. The characteristics of the Impact Tester comply with ASTM D 256. For the type of material that was studied, the 5 lbs hammer was employed to test all the mixed at two different temperatures. The energy dissipated by the systems itself was 0.23 J (or 0.17 ft.lbf) which is the friction correction value used in the calculations of Impact Strength in Chapter VI.

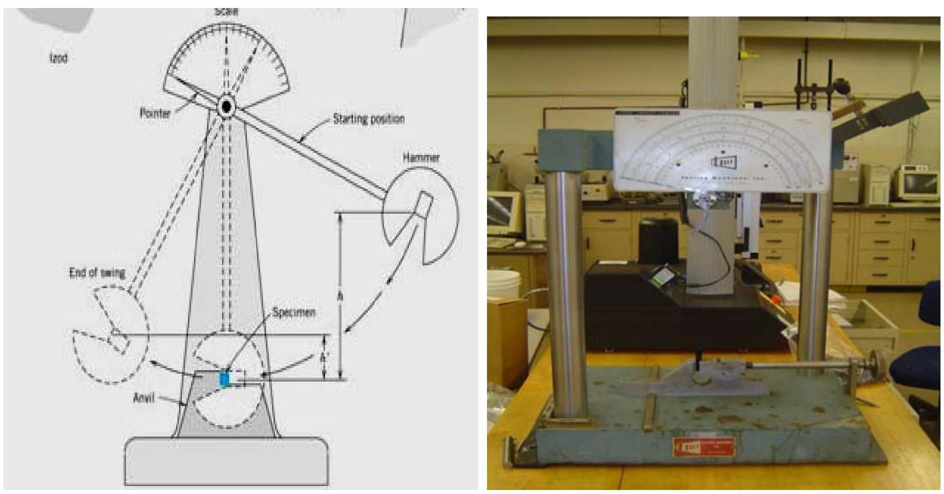


Figure 5.4 (a) Schematic picture of and (b) actual IZOD impact tester [15]

5.3 Specimen Preparation

This research used a total of eleven different mixes of materials separated in two major groups: virgin with unpainted regrind, and virgin with painted regrind. The different mixes were done by percentage of weight and are shown on table 5.2. All the specimens used in the experimental part of this research were injection-molded on the 50-ton Sumitomo machine using the parameters shown previously on Table 5.1.

Virgin with Unpainted Regrind	**Virgin with Painted Regrind**
100% Virgin	100% Virgin
80% Virgin 20% Unpainted	90% Virgin 10% Painted
50% Virgin 50% Unpainted	80% Virgin 20% Painted
20% Virgin 80% Unpainted	50% Virgin 50% Painted
10% Virgin 90% Unpainted	20% Virgin 80% Painted
100% Unpainted	100% Painted

Table 5.2 Material mixes at different levels of regrind by weight

The specimens after being injected were separated from the runners. Then, one half of the ASTM bars were cut width-wise using a paper cutter to create the bars with half the width of the originals. These shorter bars were then notched using the procedure described in Appendix I in order to comply with ASTM D 256. Finally, the specimens were stored in separate hermetic (air sealed) plastic bags until testing.

Chapter VI.

Results of Experimental Study of Different Combinations of Unpainted Regrind, Painted Regrind and Virgin TPO

6.1 Introduction

In order to define the maximum amount of unpainted regrind that could be used in a new part without the mechanical properties of the mix falling below the specification limits, the molded specimens were subjected to three different tests: a Tensile Test, an Impact Test and a Flexural Test. Similarly, the same three tests were carried on in mixes with various levels of painted regrind in order to define the maximum amount of this material that could be used in the core of a co-injected part without compromising any of the specifications.

The results for the different properties tested for each one of the different mixes is included in tables and those mixes that do not satisfy an specification are shown shaded with gray. Values for a specific mix that do not satisfy certain specification are also clearly identified as “non-pass Honda”, “non-pass adjusted” or “non-pass both”

6.2 Results

6.2.1 Adjusted Specifications

After obtaining the typical values for the five different properties of the 100% Virgin material, it was clear that some of the conditions used in this research were different to those used by Honda. Consequently, a secondary group of performance measures was developed in order to make the Honda typical values equivalent to the typical values obtained in the experimental part of the research. These adjusted specifications will serve as a secondary point of reference to determine the compliance of a specific mix of material with the manufacturer specifications. In general, it is acceptable if the mix satisfies the Honda specifications, but it is better if the mix satisfies the adjusted ones. The complete table with the Honda specifications and typical values, the typical values obtained experimentally, and the adjusted specifications is shown in Table 6.1

Property		Units (SI)	Honda Specification	Honda Typical Value	OSU Typical Value	Adjusted Specification
Impact Strength	23 C	J/m	No Break	No Break	No Break	No Break
	- 30 C		>59	70	11.476	>9.67
Tensile Strength		MPa	>15.7	16.5	19.27	>18.34
Tensile Elongation at Break		%	>200	425	482.115	>226.88
Flexural Strength		MPa	>17.6	28	29.362	>18.46
Flexural Modulus			>1470	1490	1496.813	>1476.72

Table 6.1 Comparison among typical values, and Honda and adjusted specifications

6.2.2 Tensile Test

6.2.2.1 Tensile Strength

Tensile Strength (TS) is defined as the engineering stress value at the point where the load reaches a maximum value. For this part of the experiment, ten specimens of each one of the main eleven mixes were tested whenever possible. Figure 6.1 shows the sample output for the tensile test of the 100% virgin mix. Note that the output includes the tensile strengths for each one of the specimens in pounds-per-squared-inch (inside circle) and the elongation at break percentages (inside rectangle). The summary of the results for TS is shown in Table 6.2for all the mixes. The original complete outputs for all the different mixes are included in Appendix III.

According to the results from Table 6.2 and only based on Tensile Strength results, the maximum percentage of unpainted regrind that can be used in a new part without falling below the critical limit is 80%. Similarly, the maximum percentage of painted material that could be used in a new part falls somewhere close to 10%. The exact percentage has not been defined due to time constraints and an unusual behavior of the material at higher levels of painted regrind. This unusual behavior perhaps could be explained by the reinforcing effect of paint chips in the TPO at high levels of painted regrind.

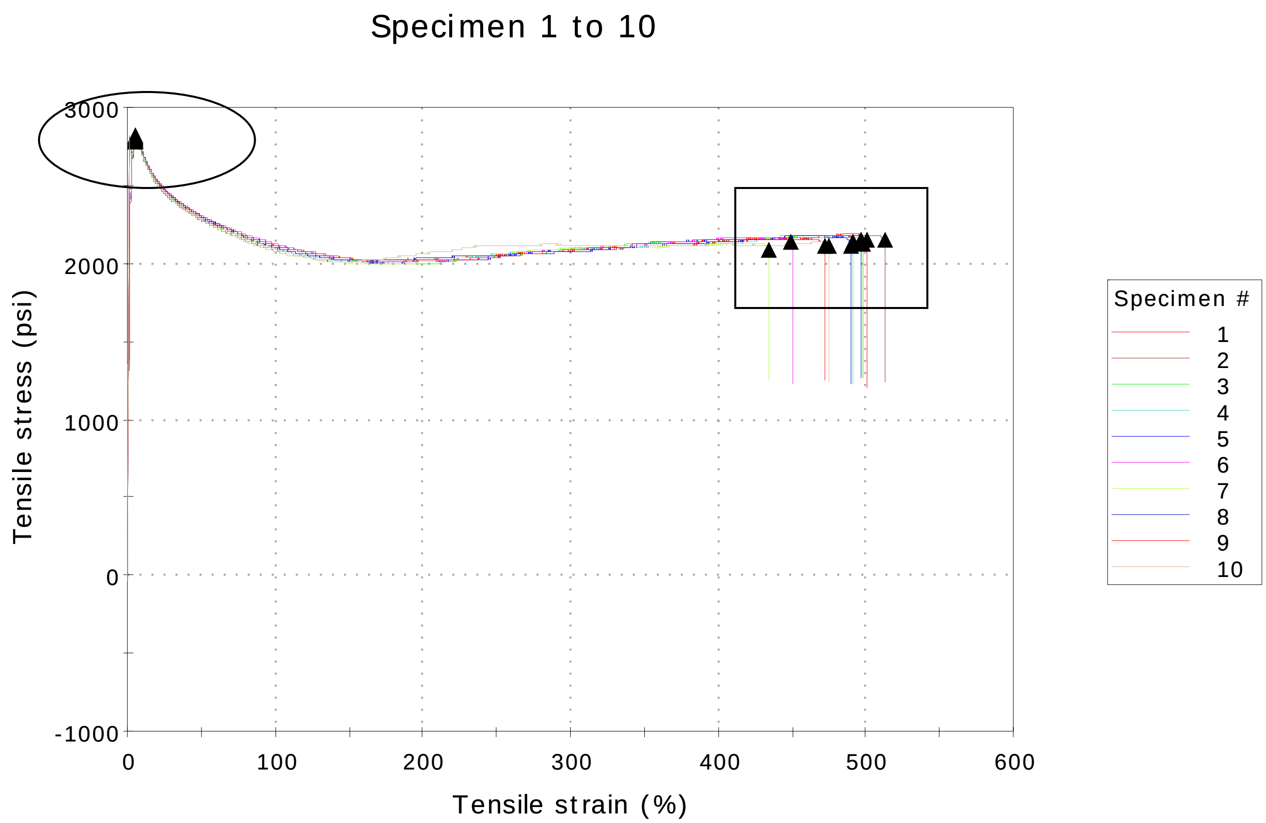


Figure 6.1 Stress-Strain graph for 100% virgin material

VIRGIN VS UNPAINTED REGRIND		Tensile Strength (MPa)
Honda Specification		>15.7
Adjusted Specification		>18.34
100% Virgin	Mean	19.27
	Std. Dev	0.08683
80% Virgin 20% Unpainted	Mean	19.082
	Std. Dev	0.14316
50% Virgin 50% Unpainted	Mean	18.634
	Std. Dev	0.099
20% Virgin 80% Unpainted	Mean	19.439
	Std. Dev	0.09209
10% Virgin 90% Unpainted	Mean	(non-pass adjusted) 18.142
	Std. Dev	0.27369
100% Unpainted	Mean	19.045
	Std. Dev	0.07961

(a)

VIRGIN VS PAINTED REGRIND		Tensile Strength (MPa)
Honda Specification		>15.7
Adjusted Specification		>18.34
100% Virgin	Mean	19.27
	Std. Dev	0.08683
90% Virgin 10% Painted	Mean	(non-pass adjusted) 17.741
	Std. Dev	0.09885
80% Virgin 20% Painted	Mean	19.117
	Std. Dev	0.0652
50% Virgin 50% Painted	Mean	18.491
	Std. Dev	0.51871
20% Virgin 80% Painted	Mean	18.969
	Std. Dev	0.07666
100% Painted	Mean	18.753
	Std. Dev	0.11998

(b)

Table 6.2. Comparison of Tensile Strengths for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

6.2.2.2 Tensile Elongation at Break

Tensile Elongation at Break or Fracture Strain is the strain calculated immediately before failure. The tensile test was used also to obtain the strain values at break and Figure 6.1 shows a sample of the output file. Ten specimens of each one of the mixes were tested and the strain at break was defined as a sudden drop in the stress value of more than 25% between recording points. Table 6.3 shows the average values and standard deviations for the tensile elongation at break values of the eleven main mixes.

Based on the Tensile Elongation at Break results, the maximum amount of unpainted regrind material that can be used in a new part is 90%. Similarly, the maximum amount of painted regrind that can be used is less than 10%.

VIRGIN VS REGRIND		**Tensile Elongation at Break (%)**
Honda Specification		>200
Adjusted Specification		>226.88
100% Virgin	Mean	482.115
	Std. Dev	24.56184
80% Virgin 20% Unpainted	Mean	317.088
	Std. Dev	127.5348
50% Virgin 50% Unpainted	Mean	549.021
	Std. Dev	21.75107
20% Virgin 80% Unpainted	Mean	367.917
	Std. Dev	96.83776
10% Virgin 90% Unpainted	Mean	565.891
	Std. Dev	28.01929
100% Unpainted	Mean	(Non-pass both) 162.605
	Std. Dev	23.18531

(a)

VIRGIN VS PAINTED		**Tensile Elongation at Break (%)**
Honda Specification		>200
Adjusted Specification		>226.88
100% Virgin	Mean	482.115
	Std. Dev	24.56184
90% Virgin 10% Painted	Mean	290.358
	Std. Dev	102.70314
80% Virgin 20% Painted	Mean	(Non-pass both) 102.113
	Std. Dev	39.50774
50% Virgin 50% Painted	Mean	(Non-pass both) 78.775
	Std. Dev	9.09254
20% Virgin 80% Painted	Mean	(Non-pass both) 51.455
	Std. Dev	9.66912
100% Painted	Mean	(Non-pass both) 49.859
	Std. Dev	11.00217

(b)

Table 6.3 Comparison of Tensile Elongation at break values for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

6.2.3 Impact Test

6.2.3.1 Impact Strength

The Impact Strength is defined as the energy required for fracturing a specimen subjected to shock loading. More specifically, it is the energy required to break specimens in which there is a v-notch to create an initial stress point. In this part of the experiment, ten specimens were tested for each one of the mixes at two different temperature levels: 23°C [Table 6.4] and -30°C [Table 6.5]. According to ASTM D 256, the impact strength values are reported for complete breaks only. However, the resulting values for impact strength for non-break cases are reported for reference in Table 6.4

Consequently, the results of the impact test show that it is feasible to use any amount of unpainted regrind material without falling below the specifications. In contrast, less than twenty percent of painted regrind can be used. These results agree closely with the results from the tensile tests.

The results shown in Table 6.4 and Table 6.5 set the maximum allowable percentage of unpainted regrind to 90% and for painted regrind to 10%. These resulting percentages agree with those obtained on section 6.2.2.

VIRGIN VS UNPAINTED REGRIND AT 23 °C		Impact Strength (J/m)	Type of Break
Honda Specification			No Break
Adjusted Specification			No Break
100% Virgin	Mean	114.50	No Break
	Std. Dev	4.891	
80% Virgin 20% Unpainted	Mean	110.36	No Break
	Std. Dev	7.983	
50% Virgin 50% Unpainted	Mean	115.70	No Break
	Std. Dev	12.629	
20% Virgin 80% Unpainted	Mean	125.71	No Break
	Std. Dev	8.124	
10% Virgin 90% Unpainted	Mean	Not Available	N/A
	Std. Dev		
100% Unpainted	Mean	128.24	No Break
	Std. Dev	9.660	

(a)

VIRGIN VS PAINTED REGRIND AT 23 °C		Impact Strength (J/m)	Type of Break
Honda Specification			No Break
Adjusted Specification			No Break
100% Virgin	Mean Std. Dev	114.50 4.891	No Break
80% Virgin 20% Painted	Mean Std. Dev	92.61 14.553	No Break
50% Virgin 50% Painted	Mean Std. Dev	90.34 13.121	No Break
20% Virgin 80% Painted	Mean Std. Dev	77.53 9.147	No Break
10% Virgin 90% Painted	Mean Std. Dev	Not Available	N/A
100% Painted	Mean Std. Dev	70.86 10.256	No Break

(b)

Table 6.4 Results of Impact Test at 23°C for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

VIRGIN VS UNPAINTED REGRIND AT -30 °C		Impact Strength (J/m)	Type of Break
Honda Specification		>59	
Adjusted Specification		>9.67	
100% Virgin	Mean Std. Dev	11.4764114 2.0091	Complete
80% Virgin 20% Unpainted	Mean Std. Dev	10.4088382 1.51501	Complete
50% Virgin 50% Unpainted	Mean Std. Dev	11.3429647 1.572684	Complete
20% Virgin 80% Unpainted	Mean Std. Dev	12.4105379 2.516294	Complete
10% Virgin 90% Unpainted	Mean Std. Dev	Not Available	N/A
100% Unpainted	Mean Std. Dev	13.6115577 3.547439	Complete

(a)

VIRGIN VS PAINTED REGRIND AT -30 °C		Impact Strength (J/m)	Type of Break
Honda Specification		>59	
Adjusted Specification		>9.67	
100% Virgin	Mean	11.4764114	Complete
	Std. Dev	2.0091	
80% Virgin 20% Painted	Mean	8.27369191	Complete
	Std. Dev	1.866134	(non-pass both)
50% Virgin 50% Painted	Mean	10.0084983	Complete
	Std. Dev	1.296868	
20% Virgin 80% Painted	Mean	10.6757315	Complete
	Std. Dev	1.989305	
10% Virgin 90% Painted	Mean	Not Available	N/A
	Std. Dev		
100% Painted	Mean	12.0101979	Complete
	Std. Dev	2.516294	

(b)

Table 6.5 Results of Impact Test at -30°C for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

6.2.4 Three-Point Bending Test

6.2.4.1 Flexural Strength

Flexural Strength is defined as ability of a material to withstand bending, expressed as the tensile stress of the outermost fibers of a bent test sample at a specified deflection level. With plastics, this value is usually higher than the straight tensile strength. In this section, ten specimens of each one of the different mixes were tested using the 3-point bend fixture and following ASTM D 790. Table 6.6 summarizes the results.

The experimental results obtained in this section are very satisfactory. In other words, every one of the mixes of both unpainted regrind and painted regrind satisfied both specifications. Accordingly, it has been found that flexural strength does not limit the amount of recycled bumper that Honda can use.

VIRGIN VS UNPAINTED REGRIND		Flexural Strength (MPa)
Honda Specification		>17.6
Adjusted Specification		>18.46
100% Virgin	Mean	29.362
	Std. Dev	0.154
80% Virgin 20% Unpainted	Mean	32.9
	Std. Dev	0.134
50% Virgin 50% Unpainted	Mean	27.331
	Std. Dev	0.133
20% Virgin 80% Unpainted	Mean	30.069
	Std. Dev	0.237
10% Virgin 90% Unpainted	Mean	26.874
	Std. Dev	0.102
100% Unpainted	Mean	29.354
	Std. Dev	0.161

(a)

VIRGIN VS PAINTED REGRIND		Flexural Strength (MPa)
Honda Specification		>17.6
Adjusted Specification		>18.46
100% Virgin	Mean	29.362
	Std. Dev	0.154
90% Virgin 10% Painted	Mean	26.467
	Std. Dev	0.397
80% Virgin 20% Painted	Mean	33.09
	Std. Dev	0.17
50% Virgin 50% Painted	Mean	27.231
	Std. Dev	0.277
20% Virgin 80% Painted	Mean	29.667
	Std. Dev	0.225
100% Painted	Mean	29.039
	Std. Dev	0.511

(b)

Table 6.6 Flexural Strength results for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

6.2.4.2 Flexural Modulus

Flexural Modulus is an engineering measurement which determines how much a sample will bend when a given load is applied. It is defined as the ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.

This last experimental section was carried on following ASTM D 790. Ten specimens were tested for each different material mix. Unlike the results for flexural strength, the results of flexural modulus are highly ambiguous. Due to high random scatter of the obtained values, It was not possible to find a relationship between amount of recycled material and its effect on flexural modulus.

In the case of the virgin and unpainted regrind mixes, the flexural Modulus resulting values agree with the previous results except on the 50% Virgin-50%. Furthermore, in the case of the mixes with unpainted regrind, the results of flexural modulus agree with the results from other tests setting the maximum allowable percentage of painted material below 10%.

VIRGIN VS UNPAINTED REGRIND		Flexural Modulus (MPa)
Honda Specification		>1470
Adjusted Specification		>1476.72
100% Virgin	Mean	1496.813
	Std. Dev	49.982
80% Virgin 20% Unpainted	Mean	1809.096
	Std. Dev	155.278
50% Virgin 50% Unpainted	Mean	(non-pass both)1264.339
	Std. Dev	60.876
20% Virgin 80% Unpainted	Mean	1558.094
	Std. Dev	52.76
10% Virgin 90% Unpainted	Mean	(non-pass both) 1229.744
	Std. Dev	55.412
100% Unpainted	Mean	(non-pass both) 1372.225
	Std. Dev	56.725

(a)

VIRGIN VS PAINTED REGRIND		Flexural Modulus (MPa)
Honda Specification		>1470
Adjusted Specification		>1476.72
100% Virgin	Mean	1496.813
	Std. Dev	49.982
90% Virgin 10% Painted	Mean	(non-pass both) 1394.57
	Std. Dev	102.526
80% Virgin 20% Painted	Mean	1698.131
	Std. Dev	65.576
50% Virgin 50% Painted	Mean	(non-pass both) 1427.374
	Std. Dev	56.051
20% Virgin 80% Painted	Mean	1569.325
	Std. Dev	64.175
100% Painted	Mean	(non-pass both) 1412.99
	Std. Dev	66.377

(b)

Table 6.6 Flexural Strength results for (a) Virgin and Unpainted Regrind, (b) Virgin and Painted Regrind

6.3 Conclusion

The results of the three different static tests carried on the eleven different material mixes suggest that the maximum amount of unpainted regrind material that can be used in combination with virgin material to manufacture a new part without falling below the manufacturer specifications is 80%. In addition, the values of the mechanical properties of a part with a percentage of painted regrind of 10% or less do satisfy the manufacturer specifications.

Chapter VIII.
Summary and Conclusion

Industry has been moving towards more environment-friendly manufacturing processes. Automotive manufactures, for example, are trying to find new ways to reuse the scrapped generated from their production activities. The large quantities of scrap generated nowadays, call for new research in the area of recycling. One attractive process to recycle plastics is co-injection, but it is necessary to find a compromise between the amount of recycled material that can be added to the virgin and the decrease in the value of some critical mechanical properties.

7.1 Summary

A sequence of experiments to measure five different mechanical properties of eleven different material mixes was carried on. The experimental results show that virgin material can be mixed with up to 80% of unpainted regrind TPO before the properties of the part fall below manufacturer specifications. In addition, a maximum percentage of 10% painted regrind can be mixed with virgin material before the properties of the part fall below.

This means, that an automotive manufacturer can use up to 80% of recycled material in a new part and up to a 10% of painted material. While the use of unpainted regrind does not affect the surface quality of the part, the painted regrind does even at low percentages. Therefore, since the impact strength and flexural modulus are largely dependent on the skin material [16], the painted material has been found to be suitable for being a structural component of a co-injected part.

7.2 Recommendations for Future Work

This study was focused on a TPO and two different types of regrind in a simple mold cavity. The levels of regrind material were roughly done in 20% increments. The effects of the parameters of injection and the effects of the painted material on surface quality need further investigation. In addition, finer mixes of the materials should be considered to find an optimal maximum level of recycled material.

Since, it was found that painted regrind can be used as the core material for a co-injected part, further study on the interface adhesion of the virgin and painted material, the effect of grain size in the properties of the part, and the behavior of the co-injected part subjected to dynamic testing should be investigated.

Additionally, further investigation on the test methods used by the automotive manufacturer to obtain their typical values is needed to compare to the methods used in this research and look for discrepancies if they exist.

Appendixes

Appendix I

Notching of Specimens for Impact Test

In order to stick to ASTM D 256, it was necessary to make a V-shape notch in the impact specimens. The dimensions and location of the notch are clearly specified in the standard. A cutting tooth was machined out of hardened steel [Figure A.1], which along a milling machine was used to create the notches.

It is important to mention that special care has to be put in the calibration of the milling machine since the depth of the notch is critical and has to remain constant for all the testing specimens, this depth was set at 2.54 mm (0.1in). Moreover, for the sake of consistency when notching, all the specimens have to be facing the same direction and also on the same position lengthwise. In other words, the direction of the shaft on the specimen and the position of the ejector pin marks have to be the same every time.

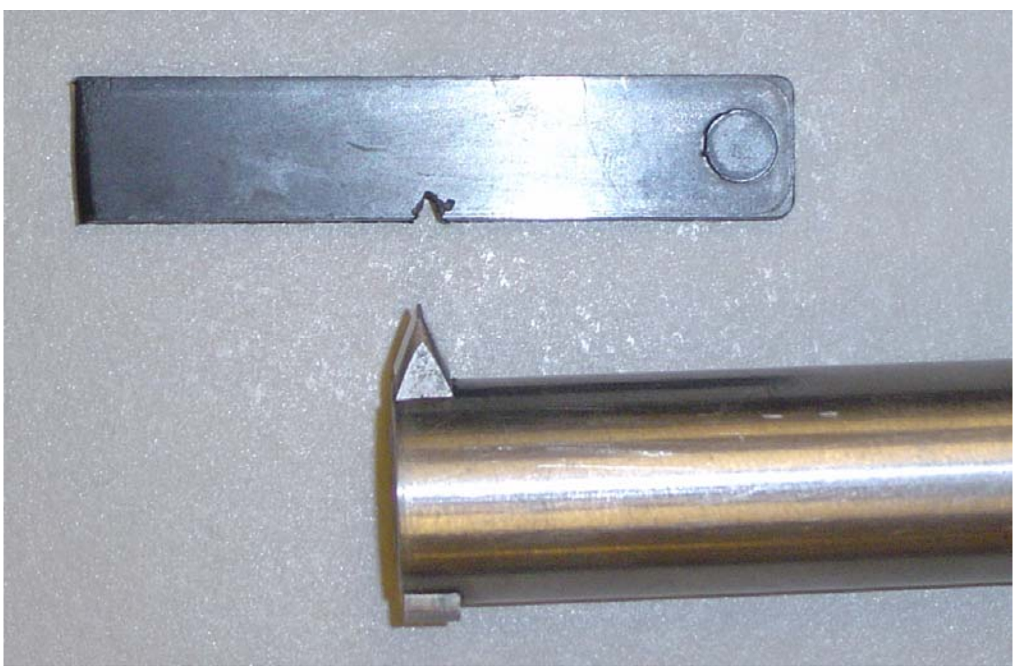


Figure A.1 Cutting tooth and V-notch in impact testing specimen. Note the position of the ejector pin mark

Appendix II

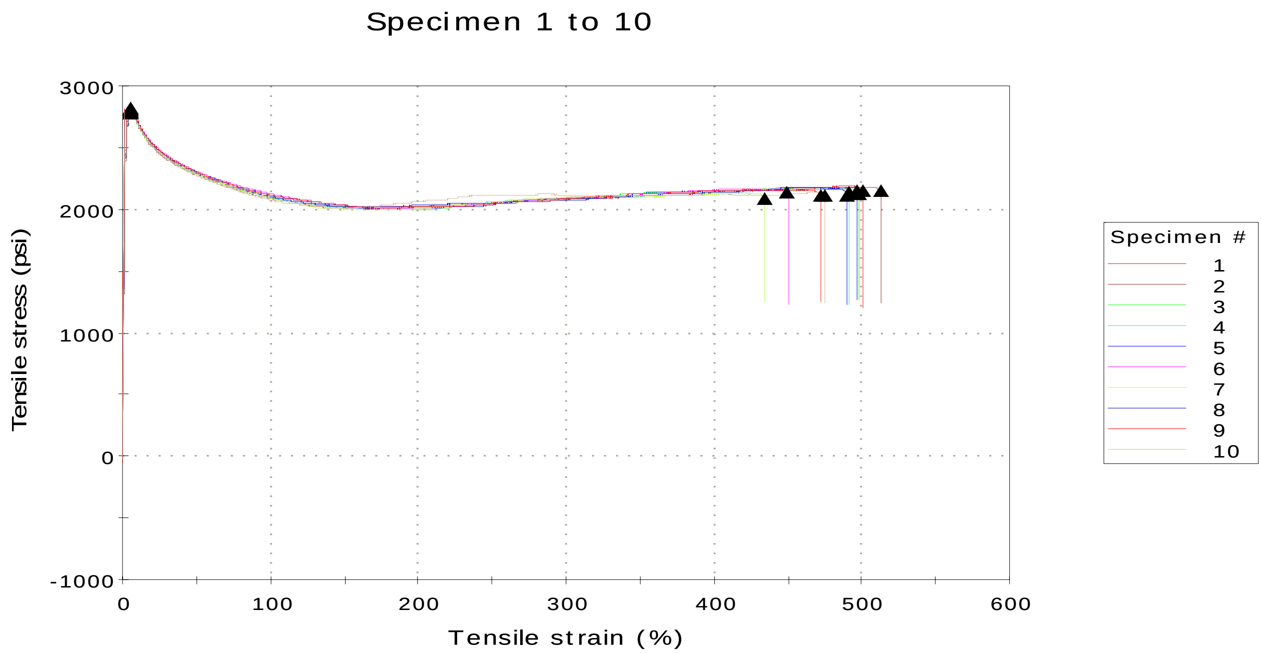
Output for Tensile Test Results

Ohio State University

ASTM D638

Material	100% Virgin
Rate 1	2.00000 in/min

Graph 1



Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	174.878	19.292	1150.647	3222.074	19.292	5.788	9.464	0.662	14.581	471.777
2	0.500	173.692	19.161	-----	1724.211	19.161	5.723	11.553	0.944	14.797	512.832
3	0.500	173.949	19.189	-----	1745.051	19.189	5.778	12.015	0.966	14.667	498.596
4	0.500	174.401	19.239	-----	1859.681	19.239	5.498	12.085	0.916	14.763	490.816
5	0.500	174.227	19.220	-----	2208.183	19.220	5.974	10.759	0.812	14.857	496.855
6	0.500	175.602	19.372	-----	2285.163	19.372	5.613	11.369	0.816	14.750	449.940
7	0.500	173.867	19.180	-----	2443.653	19.180	5.573	11.295	0.779	14.360	434.006
8	0.500	175.445	19.354	-----	2336.145	19.354	5.732	10.079	0.744	14.603	490.088
9	0.500	175.961	19.411	-----	2168.950	19.411	5.500	11.857	0.834	14.826	500.948
10	0.500	174.758	19.279	-----	2110.206	19.279	5.452	10.427	0.785	14.560	475.291
Mean	0.500	174.678	19.270	1150.647	2210.332	19.270	5.663	11.090	0.826	14.676	482.115
Maximum	0.500	175.961	19.411	1150.647	3222.074	19.411	5.974	12.085	0.966	14.857	512.832
Minimum	0.500	173.692	19.161	1150.647	1724.211	19.161	5.452	9.464	0.662	14.360	434.006
Standard Deviation	0.00000	0.78711	0.08683	-----	432.94683	0.08683	0.16443	0.88100	0.09413	0.15283	24.56184
Mean + 3 SD	0.500	177.039	19.530	-----	3509.172	19.530	6.156	13.733	1.108	15.135	555.801
Mean - 3 SD	0.500	172.317	19.009	-----	911.491	19.009	5.170	8.447	0.543	14.218	408.430
Coefficient of Variation	0.00000	0.45061	0.45061	-----	19.58741	0.45061	2.90358	7.94390	11.39910	1.04133	5.09460

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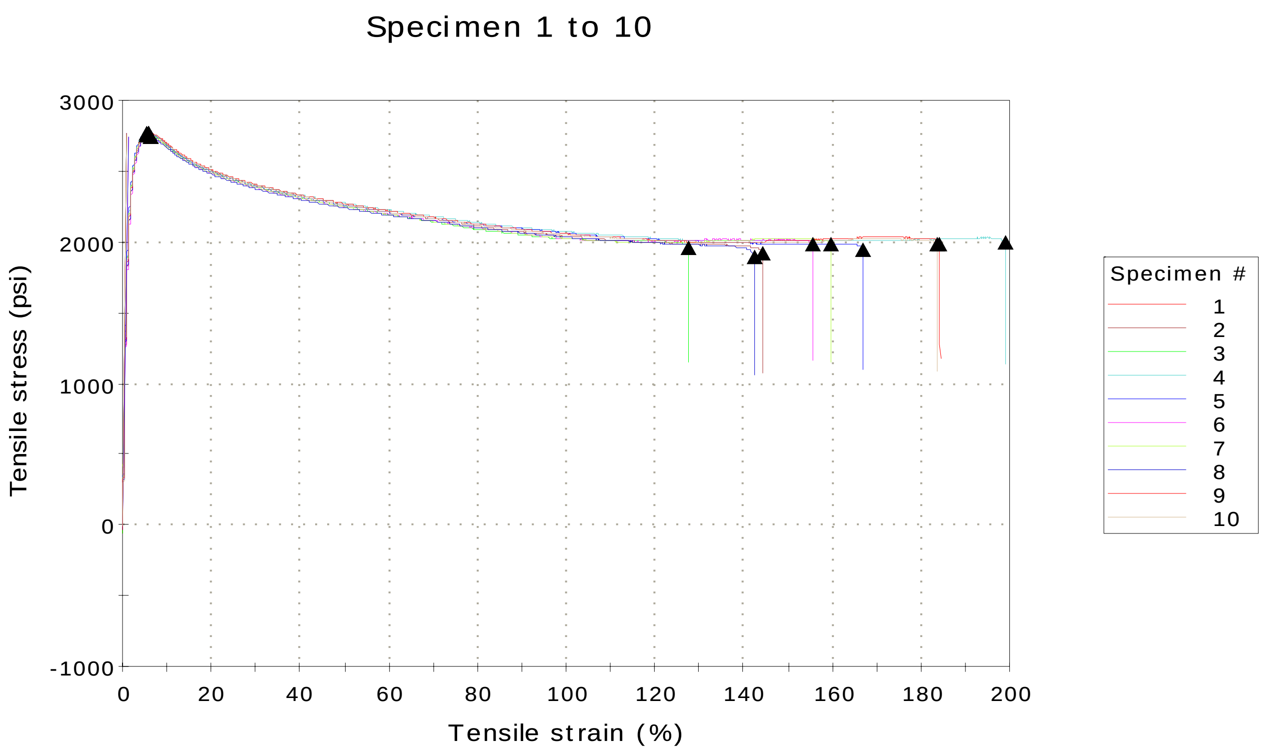
ASTM D638

Material	100% Unpainted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
2	0.500	173.055	19.091	-----	1926.426	19.091	6.006	10.220	0.827	13.231	144.435
3	0.500	172.470	19.026	-----	2478.399	19.026	5.631	9.918	0.724	13.532	127.494
4	0.500	173.369	19.125	-----	2149.990	19.125	5.633	10.548	0.793	13.751	199.093
5	0.500	173.231	19.110	-----	2213.088	19.110	5.727	10.892	0.800	13.419	166.939
6	0.500	171.528	18.922	-----	1796.119	18.922	6.120	10.544	0.881	13.670	155.443
7	0.500	172.582	19.039	-----	2597.506	19.039	5.689	9.279	0.683	13.674	159.640
8	0.500	171.423	18.911	-----	1770.572	18.911	6.184	11.232	0.929	13.056	142.360
9	0.500	173.200	19.107	-----	2085.626	19.107	5.977	10.369	0.813	13.715	184.292
10	0.500	172.864	19.070	-----	2150.008	19.070	6.028	10.364	0.798	13.639	183.750
Mean	0.500	172.636	19.045	-----	2129.748	19.045	5.888	10.374	0.805	13.521	162.605
Maximum	0.500	173.369	19.125	-----	2597.506	19.125	6.184	11.232	0.929	13.751	199.093
Minimum	0.500	171.423	18.911	-----	1770.572	18.911	5.631	9.279	0.683	13.056	127.494
Standard Deviation	0.00000	0.72168	0.07961	-----	281.00789	0.07961	0.21767	0.55863	0.07359	0.23999	23.18531
Mean + 3 SD	0.500	174.801	19.283	-----	2972.772	19.283	6.541	12.050	1.026	14.241	232.161
Mean - 3 SD	0.500	170.471	18.806	-----	1286.725	18.806	5.235	8.698	0.585	12.801	93.049
Coefficient of Variation	0.00000	0.41804	0.41804	-----	13.19442	0.41804	3.69670	5.38492	9.13833	1.77496	14.25867

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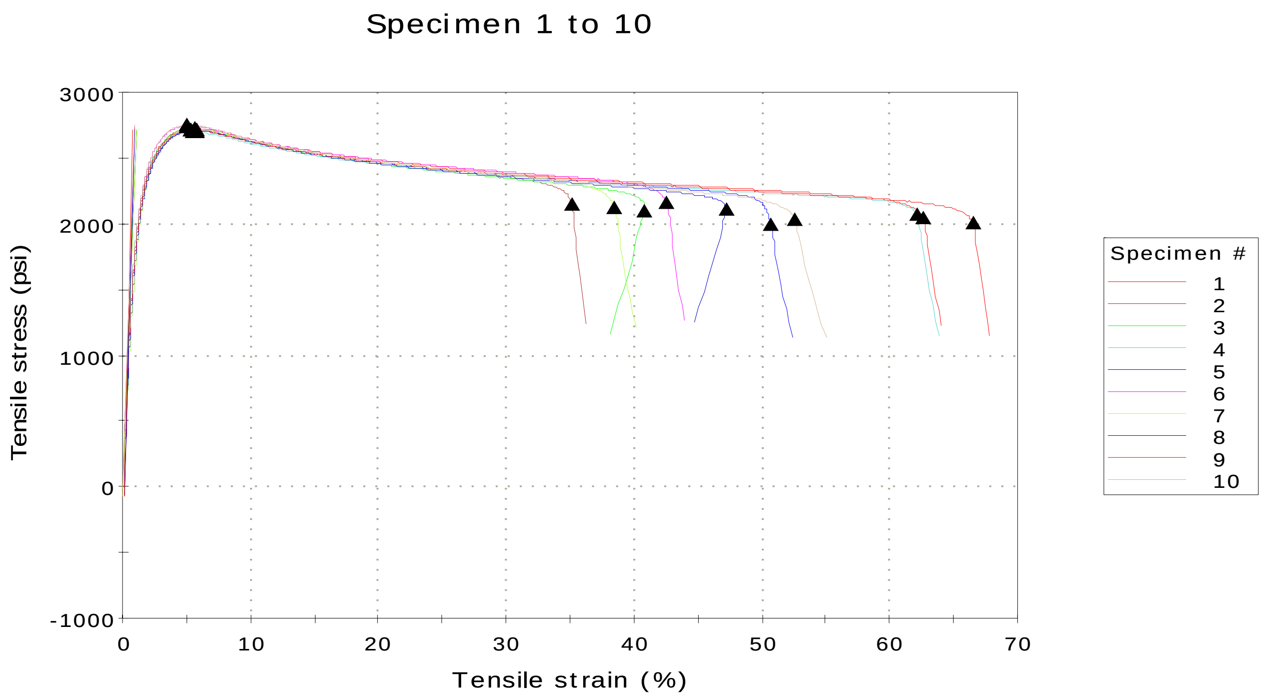
ASTM D638

Material	100% Painted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	170.384	18.796	-----	2170.499	18.796	5.708	10.796	0.802	14.126	62.605
2	0.500	169.195	18.665	-----	1793.478	18.665	5.761	11.762	0.930	14.824	35.113
3	0.500	170.072	18.762	-----	1958.805	18.762	5.316	11.207	0.848	14.472	40.808
4	0.500	168.712	18.612	-----	2444.884	18.612	5.468	10.556	0.737	14.330	62.130
5	0.500	169.235	18.669	-----	2143.492	18.669	5.629	9.460	0.741	13.747	50.712
6	0.500	171.647	18.935	-----	2103.845	18.935	5.040	10.621	0.785	14.931	42.488
7	0.500	169.692	18.720	-----	1946.344	18.720	5.586	9.646	0.785	14.686	38.450
8	0.500	169.469	18.695	-----	2044.681	18.695	5.842	10.712	0.825	14.568	47.179
9	0.500	169.434	18.691	-----	2574.508	18.691	5.367	9.607	0.688	13.841	66.506
10	0.500	172.049	18.980	-----	2029.840	18.980	5.099	11.400	0.841	14.039	52.595
Mean	0.500	169.989	18.753	-----	2121.038	18.753	5.482	10.577	0.798	14.356	49.859
Maximum	0.500	172.049	18.980	-----	2574.508	18.980	5.842	11.762	0.930	14.931	66.506
Minimum	0.500	168.712	18.612	-----	1793.478	18.612	5.040	9.460	0.688	13.747	35.113
Standard Deviation	0.00000	1.08762	0.11998	-----	233.81811	0.11998	0.27352	0.78905	0.06826	0.40920	11.00217
Mean + 3 SD	0.500	173.252	19.112	-----	2822.492	19.112	6.302	12.944	1.003	15.584	82.865
Mean - 3 SD	0.500	166.726	18.393	-----	1419.583	18.393	4.661	8.209	0.593	13.129	16.852
Coefficient of Variation	0.00000	0.63982	0.63982	-----	11.02376	0.63982	4.98971	7.46044	8.55207	2.85030	22.06670

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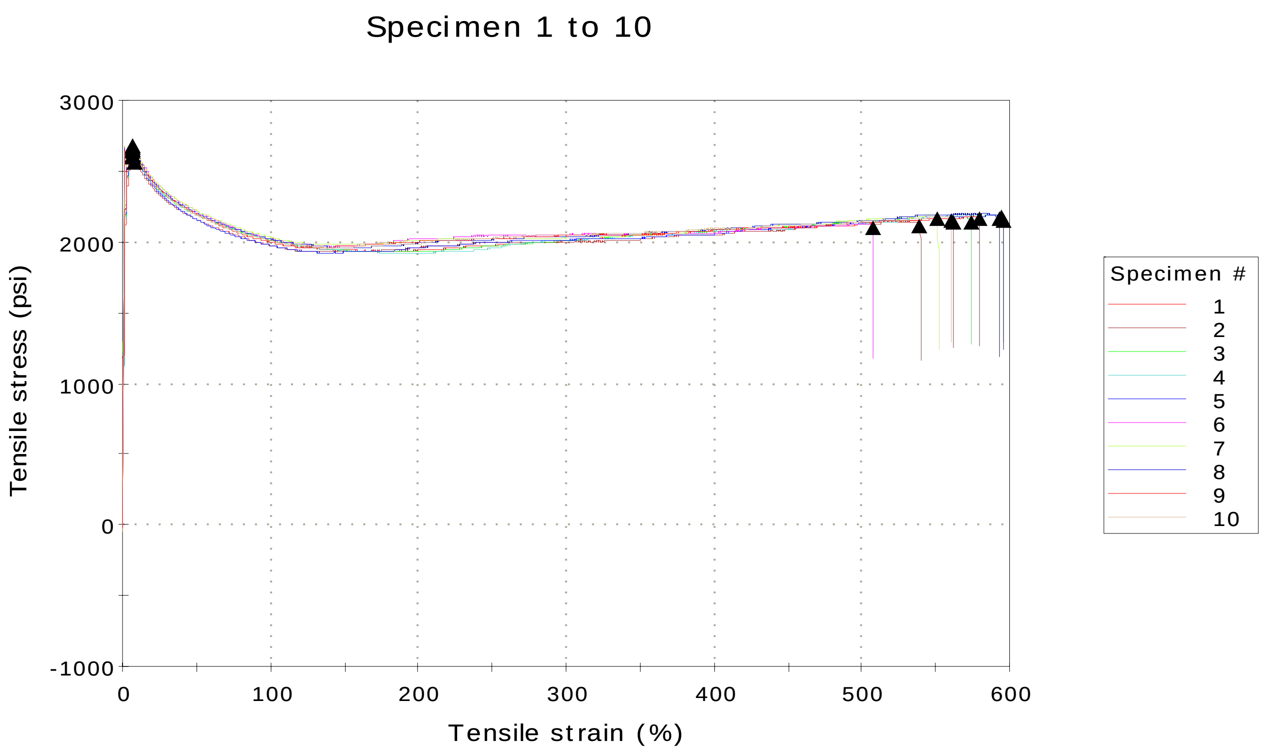
ASTM D638

Material	10% Virgin 90% Unpainted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

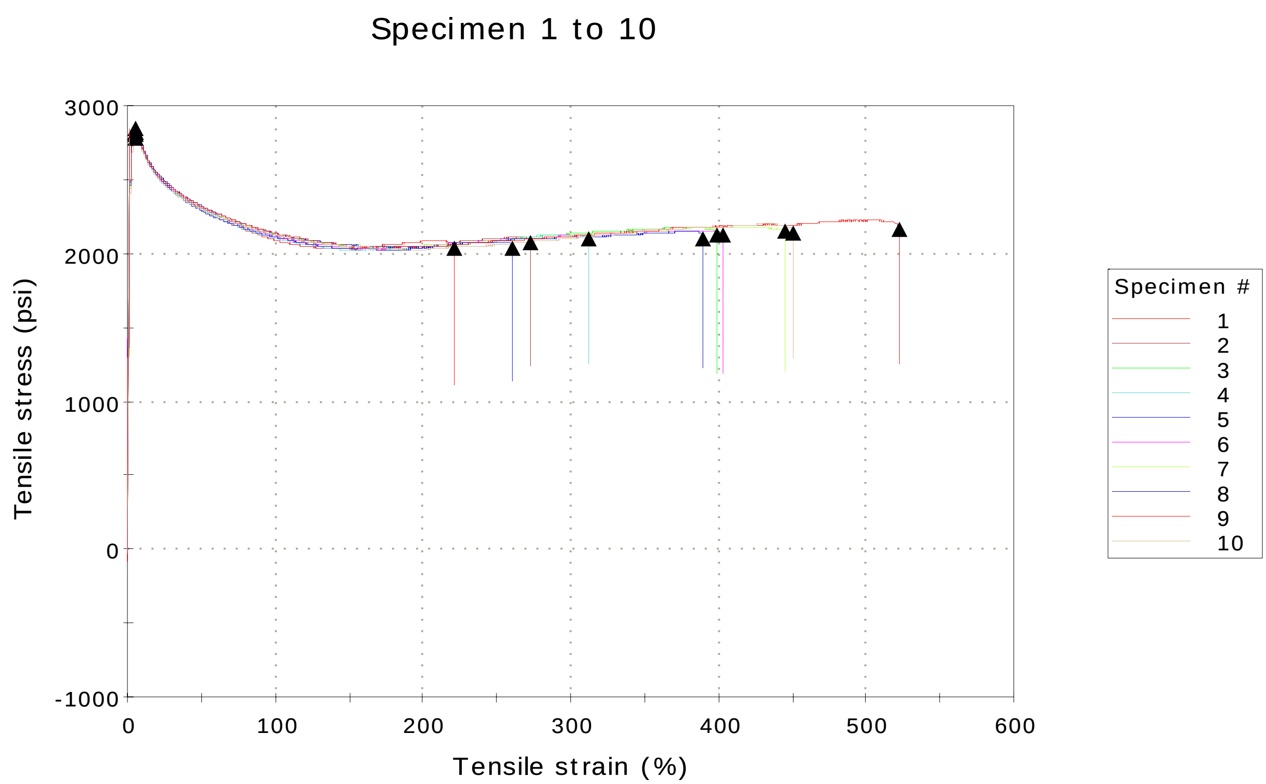
	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	163.707	18.060	-----	2380.950	18.060	7.087	9.037	0.764	14.773	562.166
2	0.500	159.895	17.639	-----	1925.207	17.639	7.583	9.434	0.861	14.554	539.585
3	0.500	162.601	17.937	-----	1861.388	17.937	6.845	10.019	0.872	14.779	573.608
4	0.500	162.936	17.974	-----	1393.656	17.974	6.940	10.930	1.071	14.996	595.162
5	0.500	163.081	17.990	-----	1695.707	17.990	6.826	10.664	0.942	14.855	596.326
6	0.500	167.752	18.506	-----	1665.523	18.506	6.729	10.764	0.951	14.434	507.724
7	0.500	167.680	18.498	-----	1833.450	18.498	6.815	10.844	0.889	14.922	551.725
8	0.500	166.358	18.352	-----	1791.893	18.352	6.472	10.061	0.880	14.923	592.846
9	0.500	165.599	18.268	-----	1749.435	18.268	6.534	10.148	0.891	14.877	579.230
10	0.500	164.912	18.192	-----	1917.133	18.192	6.776	9.575	0.834	14.854	560.540
Mean	0.500	164.452	18.142	-----	1821.434	18.142	6.861	10.147	0.895	14.797	565.891
Maximum	0.500	167.752	18.506	-----	2380.950	18.506	7.583	10.930	1.071	14.996	596.326
Minimum	0.500	159.895	17.639	-----	1393.656	17.639	6.472	9.037	0.764	14.434	507.724
Standard Deviation	0.00000	2.48094	0.27369	-----	250.30930	0.27369	0.30989	0.65299	0.08125	0.17501	28.01929
Mean + 3 SD	0.500	171.895	18.963	-----	2572.362	18.963	7.790	12.106	1.139	15.322	649.949
Mean - 3 SD	0.500	157.009	17.321	-----	1070.506	17.321	5.931	8.188	0.652	14.272	481.833
Coefficient of Variation	0.00000	1.50861	1.50861	-----	13.74243	1.50861	4.51686	6.43506	9.07345	1.18279	4.95136

Ohio State University

ASTM D638

Material	20% Virgin 80% Unpainted Regrind
Rate 1	2.00000 in/min

Graph 1



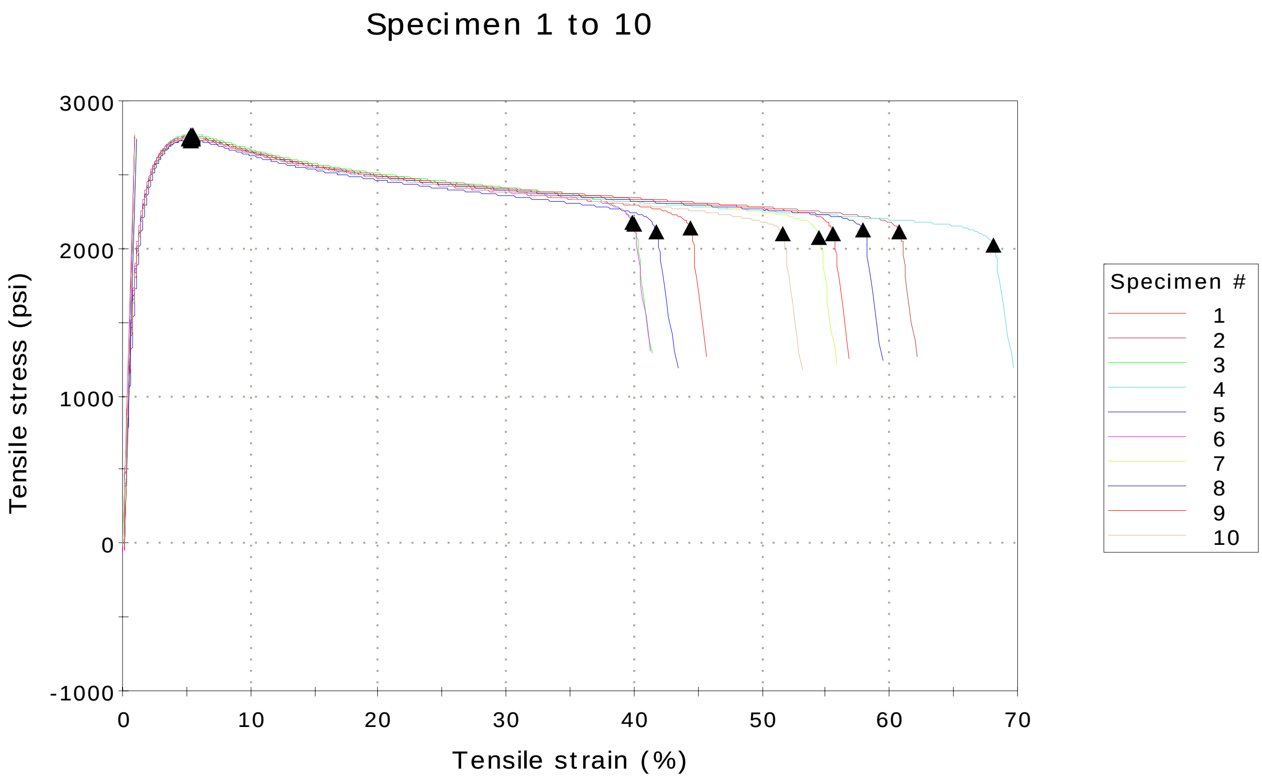
Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	177.478	19.579	-----	2483.644	19.579	5.564	10.025	0.720	13.995	221.325
2	0.500	175.764	19.390	-----	2441.813	19.390	5.255	10.010	0.709	14.333	273.406
3	0.500	176.322	19.451	-----	1784.352	19.451	5.508	11.569	0.917	14.653	399.108
4	0.500	176.186	19.436	-----	2288.267	19.436	5.355	10.669	0.764	14.455	312.731
5	0.500	176.119	19.429	-----	2135.982	19.429	5.477	11.210	0.813	14.076	260.873
6	0.500	176.264	19.445	-----	2236.934	19.445	5.646	11.064	0.793	14.681	402.569
7	0.500	176.570	19.479	-----	1635.248	19.479	5.551	11.927	0.990	14.823	445.848
8	0.500	176.646	19.487	-----	2225.388	19.487	5.597	10.344	0.775	14.459	389.997
9	0.500	176.574	19.479	-----	1933.934	19.479	5.526	11.855	0.893	14.952	522.294
10	0.500	174.213	19.219	-----	1832.334	19.219	5.853	10.842	0.878	14.777	451.017
Mean	0.500	176.214	19.439	-----	2099.790	19.439	5.533	10.951	0.825	14.521	367.917
Maximum	0.500	177.478	19.579	-----	2483.644	19.579	5.853	11.927	0.990	14.952	522.294
Minimum	0.500	174.213	19.219	-----	1635.248	19.219	5.255	10.010	0.709	13.995	221.325
Standard Deviation	0.00000	0.83474	0.09209	-----	288.69090	0.09209	0.16113	0.70211	0.09114	0.31693	96.83776
Mean + 3 SD	0.500	178.718	19.715	-----	2965.862	19.715	6.017	13.058	1.099	15.471	658.430
Mean - 3 SD	0.500	173.709	19.163	-----	1233.717	19.163	5.050	8.845	0.552	13.570	77.404
Coefficient of Variation	0.00000	0.47371	0.47371	-----	13.74856	0.47371	2.91203	6.41110	11.04223	2.18261	26.32056

Ohio State University

ASTM D638	
Material	20% Virgin 80% Painted Regrind
Rate 1	2.00000 in/min

Graph 1



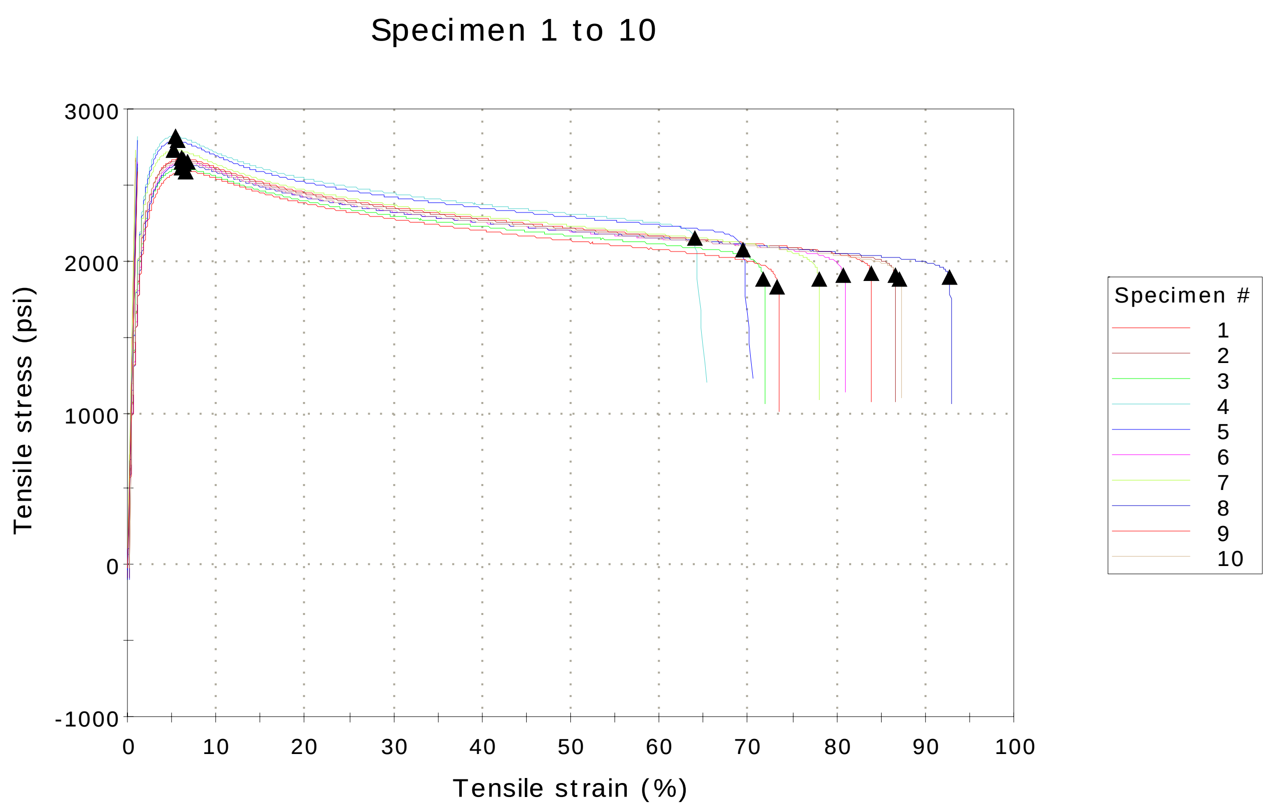
Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	171.204	18.887	-----	2072.564	18.887	5.249	11.615	0.842	14.783	44.418
2	0.500	172.850	19.068	-----	2294.291	19.068	5.524	10.342	0.751	14.577	60.798
3	0.500	173.185	19.105	-----	2237.852	19.105	5.360	10.736	0.775	14.929	39.995
4	0.500	172.143	18.990	-----	2126.006	18.990	5.377	10.970	0.811	13.948	68.081
5	0.500	170.875	18.850	-----	2416.560	18.850	5.369	10.426	0.740	14.605	41.730
6	0.500	172.159	18.992	-----	2128.573	18.992	5.396	11.431	0.805	14.999	39.898
7	0.500	171.595	18.930	-----	1752.230	18.930	5.514	12.165	0.964	14.307	54.501
8	0.500	171.700	18.941	-----	2001.362	18.941	5.570	10.029	0.796	14.676	57.952
9	0.500	172.022	18.977	-----	2222.929	18.977	5.569	10.383	0.773	14.515	55.609
10	0.500	171.793	18.952	-----	2193.499	18.952	5.314	10.495	0.777	14.521	51.569
Mean	0.500	171.953	18.969	-----	2144.587	18.969	5.424	10.859	0.803	14.586	51.455
Maximum	0.500	173.185	19.105	-----	2416.560	19.105	5.570	12.165	0.964	14.999	68.081
Minimum	0.500	170.875	18.850	-----	1752.230	18.850	5.249	10.029	0.740	13.948	39.898
Standard Deviation	0.00000	0.69491	0.07666	-----	180.69470	0.07666	0.11193	0.67766	0.06379	0.30369	9.66912
Mean + 3 SD	0.500	174.037	19.199	-----	2686.671	19.199	5.760	12.892	0.995	15.497	80.463
Mean - 3 SD	0.500	169.868	18.739	-----	1602.503	18.739	5.088	8.826	0.612	13.675	22.448
Coefficient of Variation	0.00000	0.40413	0.40413	-----	8.42562	0.40413	2.06348	6.24044	7.93924	2.08206	18.79134

ASTM D638

Material	50% Virgin 50% Painted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

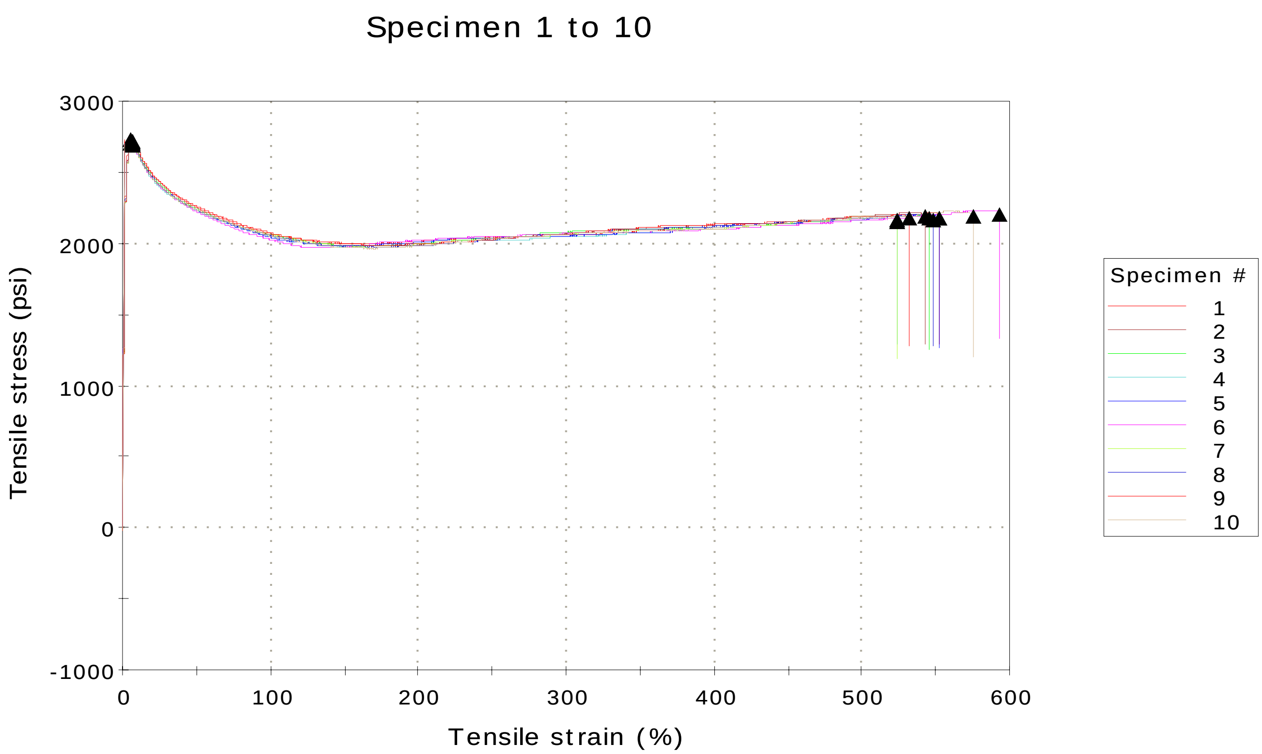
	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	167.255	18.451	-----	2290.253	18.451	6.152	9.154	0.736	13.262	83.865
2	0.500	166.609	18.380	-----	2410.743	18.380	6.257	8.913	0.714	13.184	86.618
3	0.500	163.148	17.998	-----	1909.759	17.998	6.216	10.186	0.845	13.004	71.766
4	0.500	176.178	19.435	-----	1755.876	19.435	5.505	11.739	0.934	14.866	63.947
5	0.500	174.472	19.247	-----	1713.051	19.247	5.572	11.879	0.960	14.329	69.383
6	0.500	165.739	18.284	-----	1952.570	18.284	6.722	9.242	0.793	13.106	80.801
7	0.500	170.490	18.808	-----	2268.877	18.808	5.289	10.167	0.745	12.961	78.033
8	0.500	164.795	18.180	-----	2007.180	18.180	6.293	8.764	0.762	13.053	92.769
9	0.500	161.777	17.847	-----	1733.994	17.847	6.520	9.758	0.874	12.655	73.416
10	0.500	165.685	18.278	-----	2228.281	18.278	6.053	9.758	0.759	12.982	87.154
Mean	0.500	167.615	18.491	-----	2027.058	18.491	6.058	9.956	0.812	13.340	78.775
Maximum	0.500	176.178	19.435	-----	2410.743	19.435	6.722	11.879	0.960	14.866	92.769
Minimum	0.500	161.777	17.847	-----	1713.051	17.847	5.289	8.764	0.714	12.655	63.947
Standard Deviation	0.00000	4.70203	0.51871	-----	256.72776	0.51871	0.46145	1.09102	0.08639	0.69337	9.09254
Mean + 3 SD	0.500	181.721	20.047	-----	2797.242	20.047	7.442	13.229	1.071	15.420	106.053
Mean - 3 SD	0.500	153.509	16.934	-----	1256.875	16.934	4.673	6.683	0.553	11.260	51.498
Coefficient of Variation	0.00000	2.80526	2.80526	-----	12.66504	2.80526	7.61735	10.95846	10.63657	5.19768	11.54238

Ohio State University

ASTM D638

Material	50% Virgin 50% Unpainted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

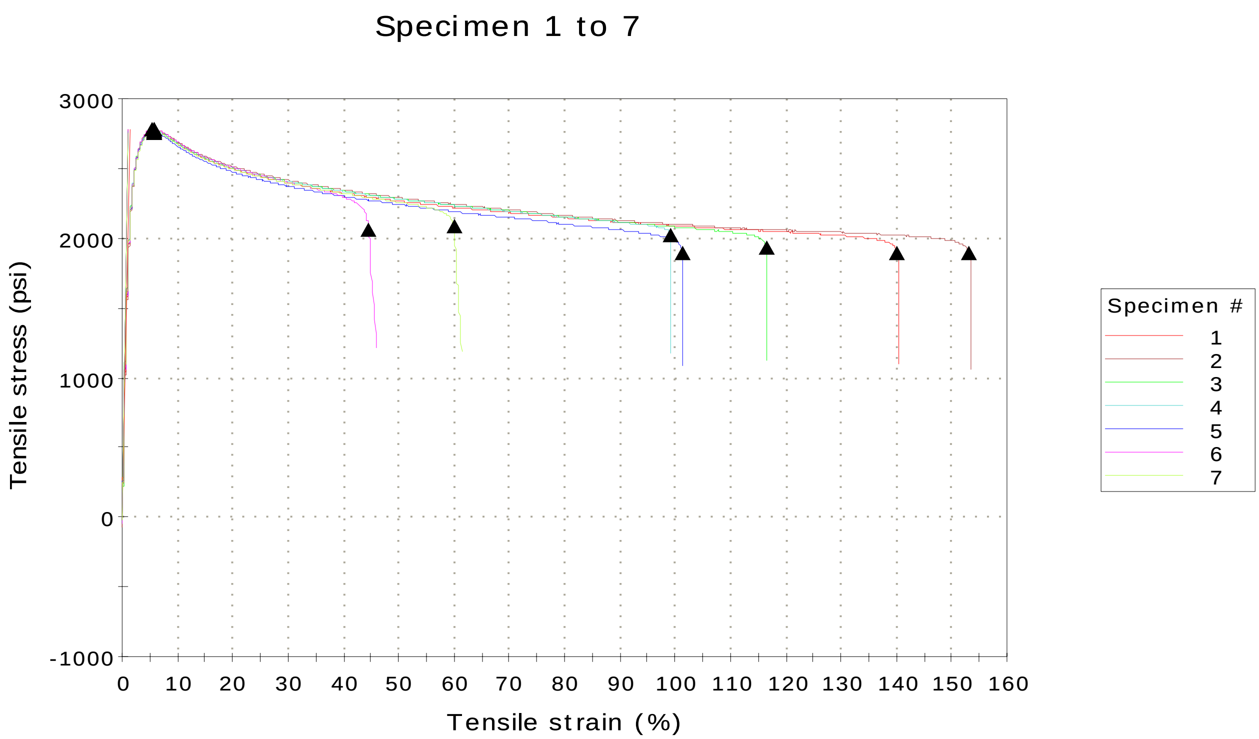
	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	170.806	18.843	-----	2002.679	18.843	6.078	9.908	0.807	15.041	552.559
2	0.500	168.541	18.593	-----	1763.619	18.593	6.448	10.553	0.907	15.060	542.792
3	0.500	169.401	18.688	-----	1890.818	18.688	6.374	10.204	0.854	14.981	545.588
4	0.500	167.979	18.531	-----	1680.644	18.531	6.251	10.873	0.938	14.962	523.916
5	0.500	168.635	18.603	-----	1883.990	18.603	6.271	10.441	0.866	14.998	552.902
6	0.500	168.051	18.539	-----	1753.395	18.539	6.229	10.861	0.915	15.175	593.176
7	0.500	168.219	18.557	-----	1717.886	18.557	6.527	10.780	0.932	14.860	524.160
8	0.500	168.811	18.623	-----	1667.304	18.623	6.451	11.220	0.960	14.921	548.705
9	0.500	169.945	18.748	-----	2131.072	18.748	6.472	9.274	0.769	15.032	531.451
10	0.500	168.720	18.613	-----	2404.000	18.613	6.098	9.076	0.719	15.122	574.965
Mean	0.500	168.911	18.634	-----	1889.541	18.634	6.320	10.319	0.867	15.015	549.021
Maximum	0.500	170.806	18.843	-----	2404.000	18.843	6.527	11.220	0.960	15.175	593.176
Minimum	0.500	167.979	18.531	-----	1667.304	18.531	6.078	9.076	0.719	14.860	523.916
Standard Deviation	0.00000	0.89741	0.09900	-----	233.98073	0.09900	0.15853	0.70839	0.07958	0.09249	21.75107
Mean + 3 SD	0.500	171.603	18.931	-----	2591.483	18.931	6.796	12.444	1.105	15.293	614.274
Mean - 3 SD	0.500	166.218	18.337	-----	1187.598	18.337	5.844	8.194	0.628	14.738	483.768
Coefficient of Variation	0.00000	0.53129	0.53129	-----	12.38294	0.53129	2.50836	6.86483	9.18145	0.61599	3.96179

Ohio State University

ASTM D638

Material	80% Virgin 20% Painted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

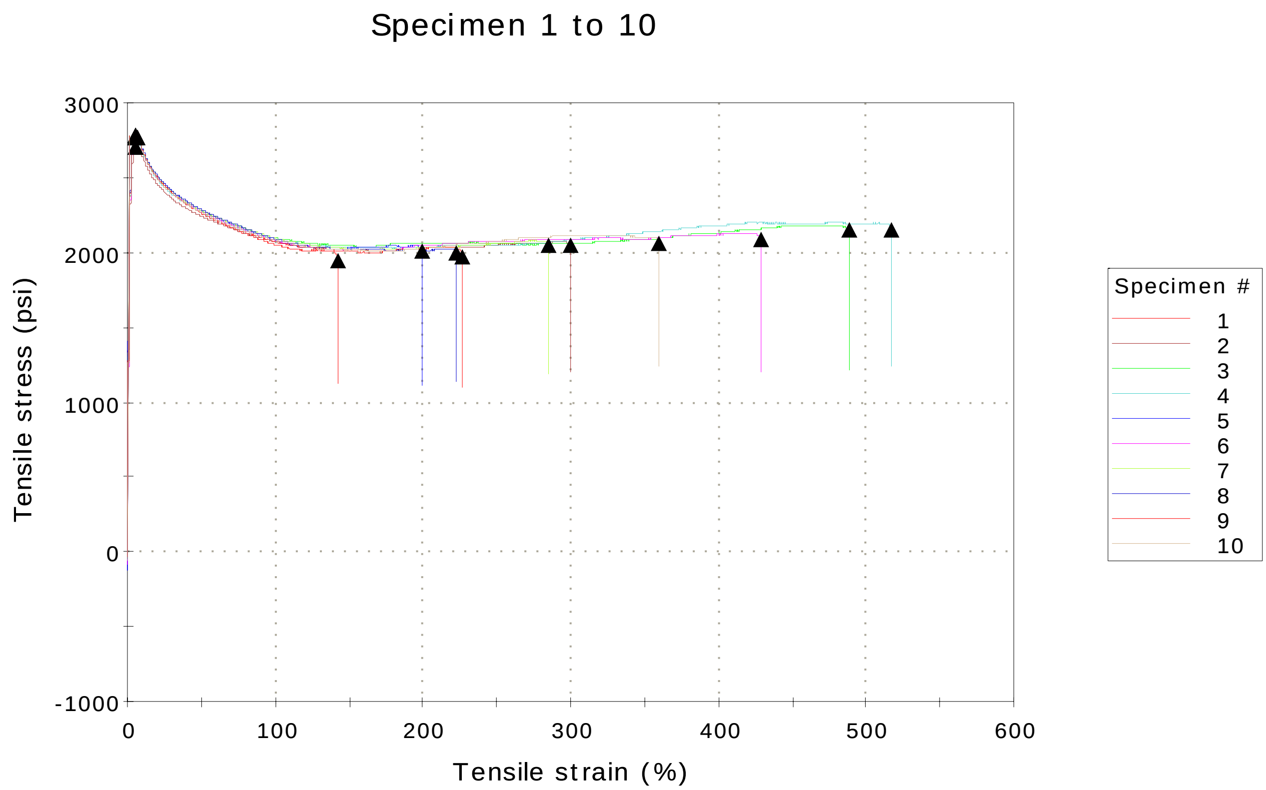
	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	173.459	19.135	-----	1502.862	19.135	5.504	12.047	1.051	13.038	140.235
2	0.500	173.968	19.191	-----	1739.736	19.191	5.881	10.693	0.896	13.068	153.192
3	0.500	173.409	19.130	-----	2156.969	19.130	5.762	10.238	0.785	13.349	116.417
4	0.500	173.135	19.100	-----	2295.070	19.100	5.634	9.721	0.733	13.986	99.050
5	0.500	172.536	19.033	-----	1762.107	19.033	5.728	10.976	0.904	13.024	101.371
6	0.500	173.964	19.191	-----	1904.569	19.191	5.662	10.276	0.830	14.237	44.574
7	0.500	172.550	19.035	-----	1912.363	19.035	5.823	10.831	0.860	14.371	59.951
Mean	0.500	173.289	19.117	-----	1896.239	19.117	5.714	10.683	0.865	13.582	102.113
Maximum	0.500	173.968	19.191	-----	2295.070	19.191	5.881	12.047	1.051	14.371	153.192
Minimum	0.500	172.536	19.033	-----	1502.862	19.033	5.504	9.721	0.733	13.024	44.574
Standard Deviation	0.00000	0.59102	0.06520	-----	266.02178	0.06520	0.12607	0.73674	0.10185	0.59721	39.50774
Mean + 3 SD	0.500	175.062	19.312	-----	2694.305	19.312	6.092	12.893	1.171	15.373	220.636
Mean - 3 SD	0.500	171.516	18.921	-----	1098.174	18.921	5.335	8.473	0.560	11.790	-16.410
Coefficient of Variation	0.00000	0.34106	0.34106	-----	14.02891	0.34106	2.20644	6.89622	11.76815	4.39717	38.69025

Ohio State University

ASTM D638

Material	80% Virgin 20% Unpainted Regrind
Rate 1	2.00000 in/min

Graph 1



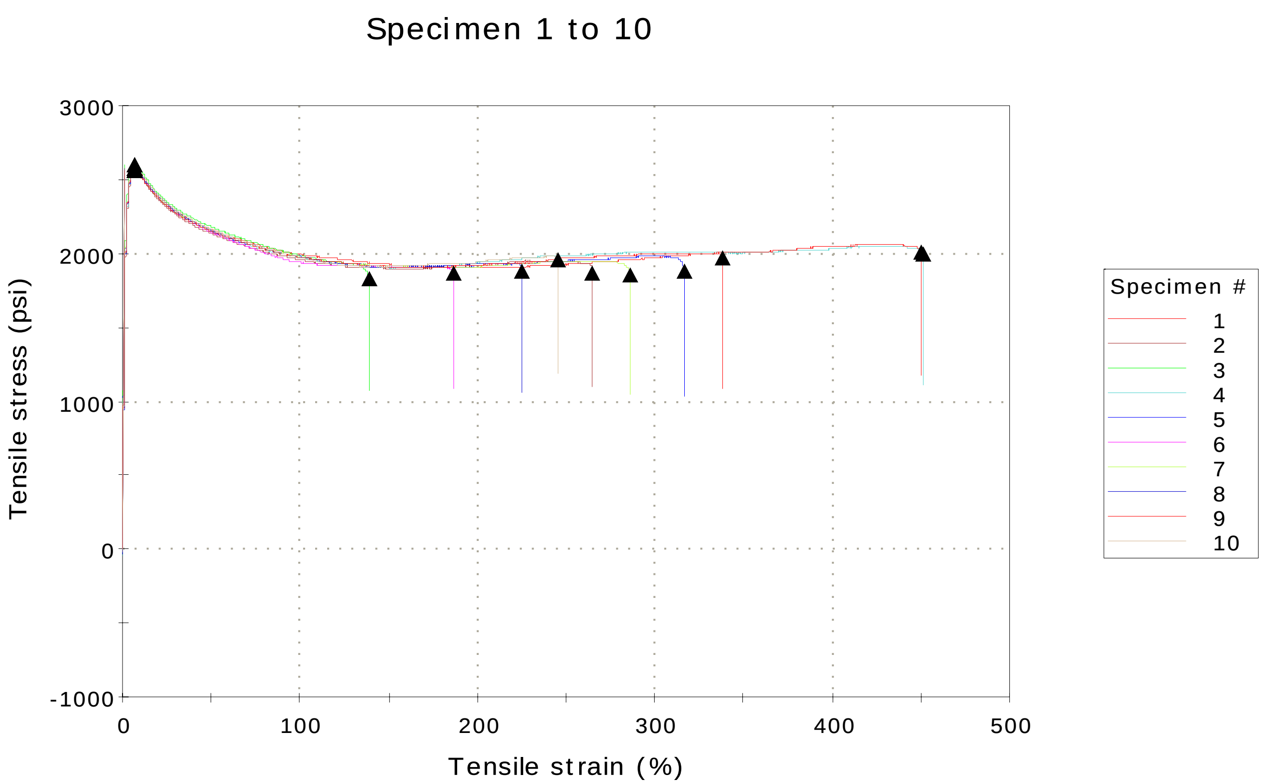
Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	173.532	19.143	-----	1736.462	19.143	5.673	11.670	0.937	13.426	142.713
2	0.500	169.411	18.689	-----	1975.812	18.689	6.079	10.254	0.826	14.133	299.993
3	0.500	173.109	19.097	-----	1816.551	19.097	5.764	10.713	0.871	14.809	488.741
4	0.500	172.892	19.073	-----	2016.378	19.073	5.563	10.111	0.794	14.862	516.841
5	0.500	173.833	19.177	-----	2345.594	19.177	5.527	10.459	0.749	13.840	199.174
6	0.500	173.069	19.092	-----	1927.270	19.092	6.069	9.665	0.803	14.347	429.178
7	0.500	173.462	19.136	-----	2257.715	19.136	5.604	9.925	0.745	14.097	285.497
8	0.500	173.337	19.122	-----	1837.712	19.122	6.168	11.651	0.921	13.742	222.238
9	0.500	173.955	19.190	-----	1659.461	19.190	5.640	11.485	0.961	13.629	227.211
10	0.500	173.189	19.106	-----	1605.702	19.106	5.723	11.449	0.980	14.195	359.291
Mean	0.500	172.979	19.082	-----	1917.866	19.082	5.781	10.738	0.859	14.108	317.088
Maximum	0.500	173.955	19.190	-----	2345.594	19.190	6.168	11.670	0.980	14.862	516.841
Minimum	0.500	169.411	18.689	-----	1605.702	18.689	5.527	9.665	0.745	13.426	142.713
Standard Deviation	0.00000	1.29775	0.14316	-----	241.61880	0.14316	0.23581	0.76615	0.08735	0.47450	127.53480
Mean + 3 SD	0.500	176.872	19.512	-----	2642.722	19.512	6.488	13.037	1.121	15.532	699.692
Mean - 3 SD	0.500	169.086	18.653	-----	1193.009	18.653	5.074	8.440	0.597	12.685	-65.517
Coefficient of Variation	0.00000	0.75024	0.75024	-----	12.59832	0.75024	4.07895	7.13479	10.17171	3.36331	40.22067

Ohio State University

ASTM D638	
Material	90% virgin 10% Painted Regrind
Rate 1	2.00000 in/min

Graph 1



Results Table 1

	Width (in)	Maximum Load (lbf)	Tensile stress at Maximum Load (MPa)	Modulus (Secant - Cursor) (MPa)	Modulus (Young's 200 psi - 1500 psi) (MPa)	Tensile Stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (%)	Tensile stress at Yield (Offset 0.2 %) (MPa)	Tensile strain at Yield (Offset 0.2 %) (%)	Tensile stress at Break (Standard) (MPa)	Tensile strain at Break (Standard) (%)
1	0.500	161.219	17.785	962.964	2231.627	17.785	7.139	8.652	0.774	13.591	338.002
2	0.500	159.839	17.633	1003.853	2834.416	17.633	7.037	8.667	0.727	12.903	264.780
3	0.500	162.978	17.979	1035.062	2093.209	17.979	6.686	9.953	0.824	12.659	138.831
4	0.500	160.225	17.675	1008.744	2433.048	17.675	7.089	9.064	0.762	13.768	451.099
5	0.500	160.384	17.693	1042.940	2019.333	17.693	6.986	9.959	0.846	12.968	316.704
6	0.500	160.639	17.721	1013.865	1723.639	17.721	7.038	10.152	0.919	12.837	186.534
7	0.500	160.667	17.724	1035.757	1819.735	17.724	6.856	10.335	0.901	12.768	286.208
8	0.500	160.807	17.740	996.055	1440.380	17.740	6.905	10.734	1.039	13.009	225.441
9	0.500	160.080	17.659	1020.163	1465.620	17.659	6.684	10.811	1.024	13.896	450.120
10	0.500	161.368	17.801	1021.746	1477.900	17.801	6.729	10.776	1.022	13.522	245.860
Mean	0.500	160.820	17.741	1014.115	1953.891	17.741	6.915	9.911	0.884	13.192	290.358
Maximum	0.500	162.978	17.979	1042.940	2834.416	17.979	7.139	10.811	1.039	13.896	451.099
Minimum	0.500	159.839	17.633	962.964	1440.380	17.633	6.684	8.652	0.727	12.659	138.831
Standard Deviation	0.00000	0.89610	0.09885	23.35625	460.12414	0.09885	0.17004	0.83854	0.11581	0.45366	102.70314
Mean + 3 SD	0.500	163.509	18.038	1084.184	3334.263	18.038	7.425	12.426	1.231	14.553	598.467
Mean - 3 SD	0.500	158.132	17.445	944.046	573.518	17.445	6.405	7.395	0.536	11.831	-17.751
Coefficient of Variation	0.00000	0.55721	0.55721	2.30312	23.54912	0.55721	2.45904	8.46114	13.10364	3.43896	35.37122

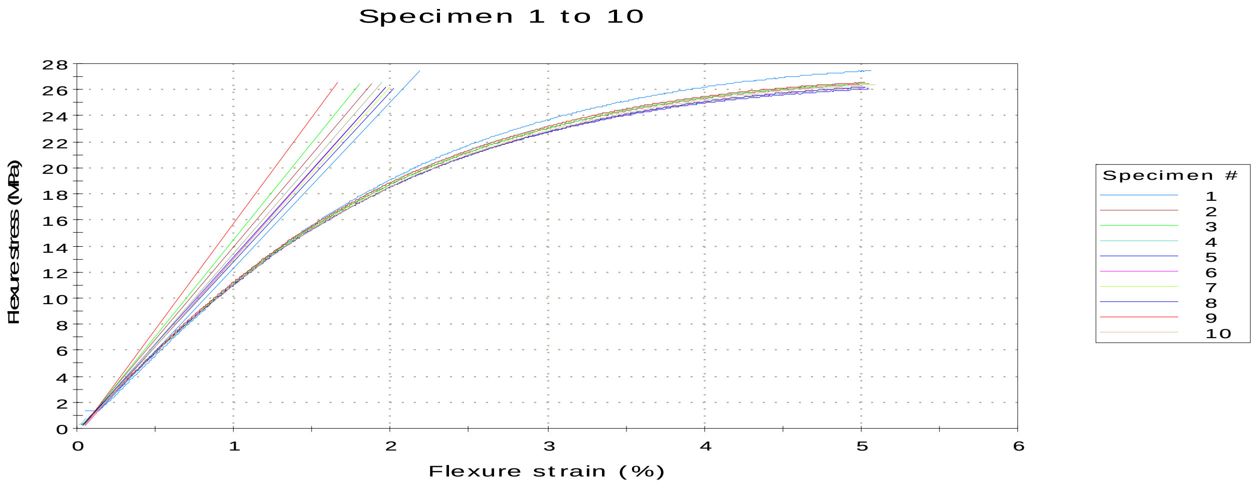
Appendix IV

Output for the Flexural Test Results

ASTM D790 Procedure B

Material Type	90% virgin 10% painted regrind

Graph 1



Results Table 1

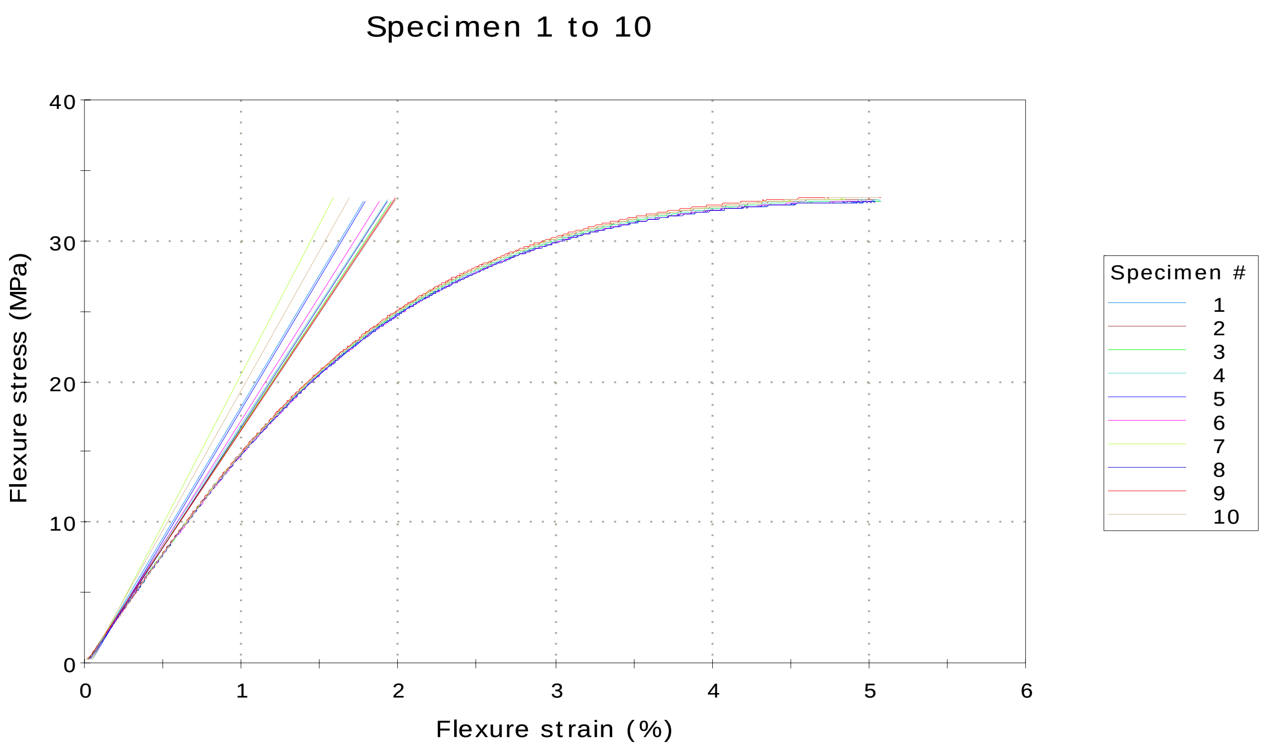
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.070	27.480	911.482	1098.977	1277.556
2	0.493	0.130	none	5.044	26.461	871.391	1172.168	1425.942
3	0.493	0.130	none	5.023	26.506	882.344	1162.856	1491.618
4	0.493	0.130	none	5.014	26.559	887.484	1173.544	1394.553
5	0.493	0.130	none	5.043	26.074	869.168	1158.686	1304.494
6	0.493	0.130	none	5.049	26.187	866.294	1159.818	1350.228
7	0.493	0.130	none	5.048	26.201	866.462	1160.696	1327.932
8	0.493	0.130	none	5.025	26.220	863.430	1160.656	1348.880
9	0.493	0.130	none	5.025	26.580	881.210	1177.608	1626.716
10	0.493	0.130	none	5.080	26.403	866.088	1147.882	1397.785
Maximum	0.493	0.130		5.080	27.480	911.482	1177.608	1626.716
Mean	0.493	0.130		5.042	26.467	876.535	1157.289	1394.570
Minimum	0.493	0.130		5.014	26.074	863.430	1098.977	1277.556
Standard Deviation	0.000	0.000		0.021	0.397	14.775	22.235	102.526

Ohio State University

ASTM D790 Procedure B

Material Type	80% Virgin 20% Unpainted Regrind

Graph 1



Results Table 1

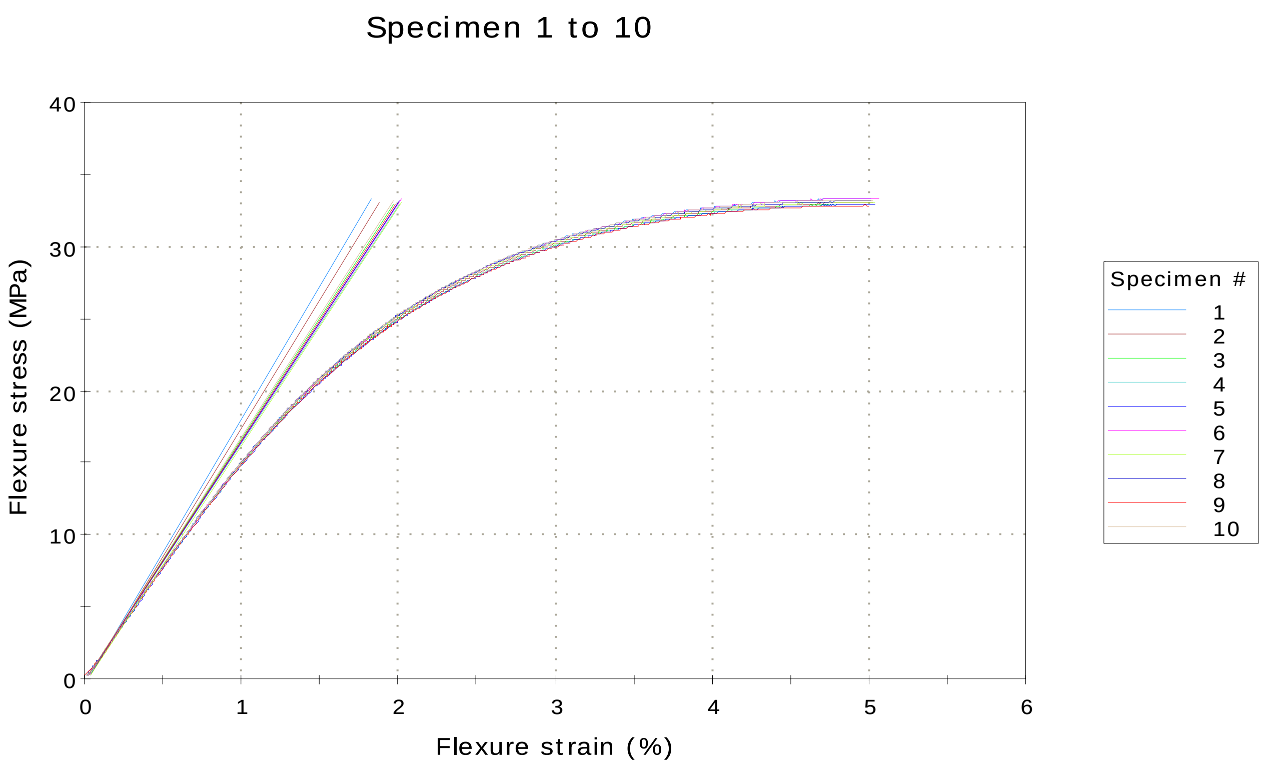
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.059	32.771	1266.428	1545.014	1868.527
2	0.493	0.130	none	5.005	32.961	1282.275	1563.868	1676.565
3	0.493	0.130	none	5.045	32.843	1272.010	1551.343	1687.642
4	0.493	0.130	none	4.947	32.888	1268.654	1549.478	1711.415
5	0.493	0.130	none	4.972	32.761	1267.634	1542.059	1862.744
6	0.493	0.130	none	5.001	32.806	1262.944	1539.114	1763.151
7	0.493	0.130	none	4.976	33.032	1281.516	1548.419	2141.151
8	0.493	0.130	none	4.977	32.760	1257.581	1543.674	1712.415
9	0.493	0.130	none	4.955	33.117	1288.300	1549.839	1682.339
10	0.493	0.130	none	5.041	33.061	1281.232	1543.300	1985.014
Maximum	0.493	0.130		5.059	33.117	1288.300	1563.868	2141.151
Mean	0.493	0.130		4.998	32.900	1272.857	1547.611	1809.096
Minimum	0.493	0.130		4.947	32.760	1257.581	1539.114	1676.565
Standard Deviation	0.000	0.000		0.039	0.134	9.950	6.921	155.278

Ohio State University

ASTM D790 Procedure B

Material Type	80% Virgin 20% Painted Regrind

Graph 1



Results Table 1

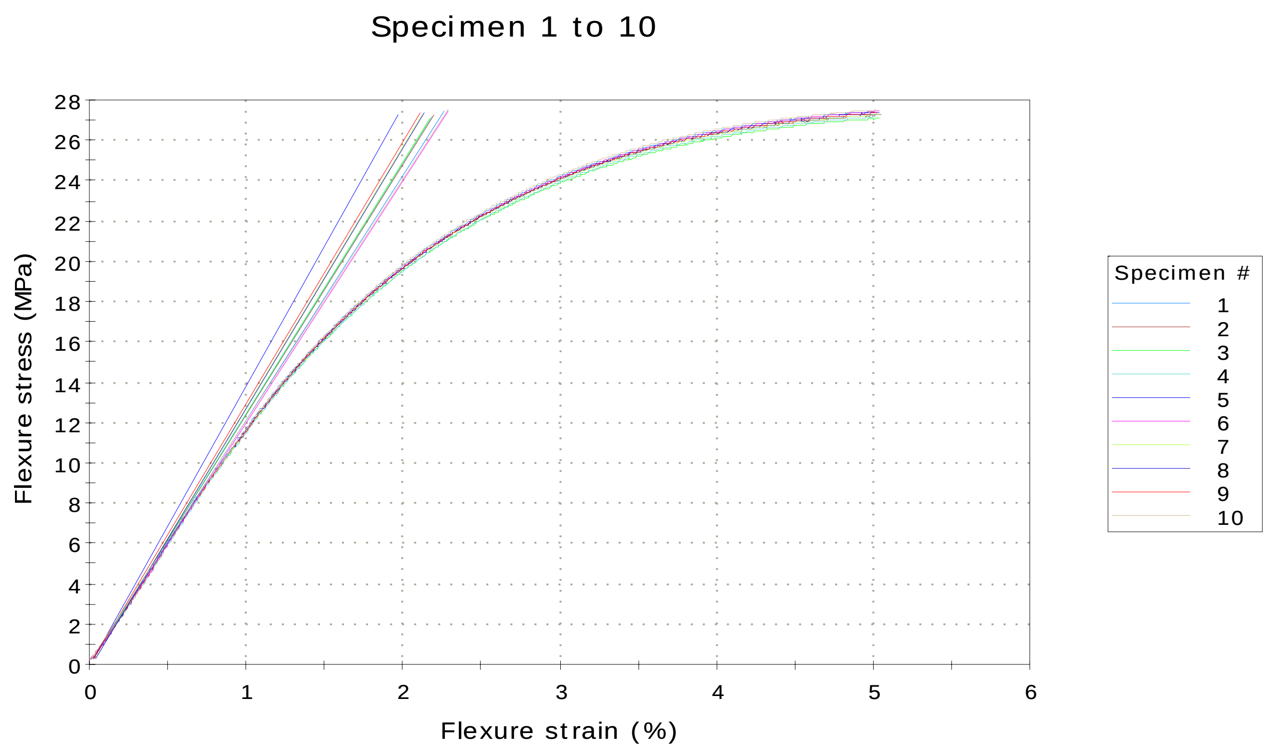
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	4.964	33.308	1294.729	1560.977	1848.357
2	0.493	0.130	none	5.001	33.052	1280.297	1559.299	1781.637
3	0.493	0.130	none	4.997	32.949	1271.548	1547.918	1687.183
4	0.493	0.130	none	4.997	32.942	1267.976	1548.070	1647.162
5	0.493	0.130	none	5.023	32.920	1271.241	1536.219	1665.380
6	0.493	0.130	none	5.052	33.351	1293.527	1553.289	1662.676
7	0.493	0.130	none	4.909	33.111	1292.384	1559.022	1653.498
8	0.493	0.130	none	4.931	33.164	1298.918	1560.717	1659.472
9	0.493	0.130	none	4.977	32.872	1270.306	1542.098	1673.482
10	0.493	0.130	none	4.990	33.229	1301.695	1559.795	1702.462
Maximum	0.493	0.130		5.052	33.351	1301.695	1560.977	1848.357
Mean	0.493	0.130		4.984	33.090	1284.262	1552.740	1698.131
Minimum	0.493	0.130		4.909	32.872	1267.976	1536.219	1647.162
Standard Deviation	0.000	0.000		0.042	0.170	13.279	8.790	65.576

Ohio State University

ASTM D790 Procedure B

Material Type	50% Virgin 50% Unpainted Regrind

Graph 1



Results Table 1

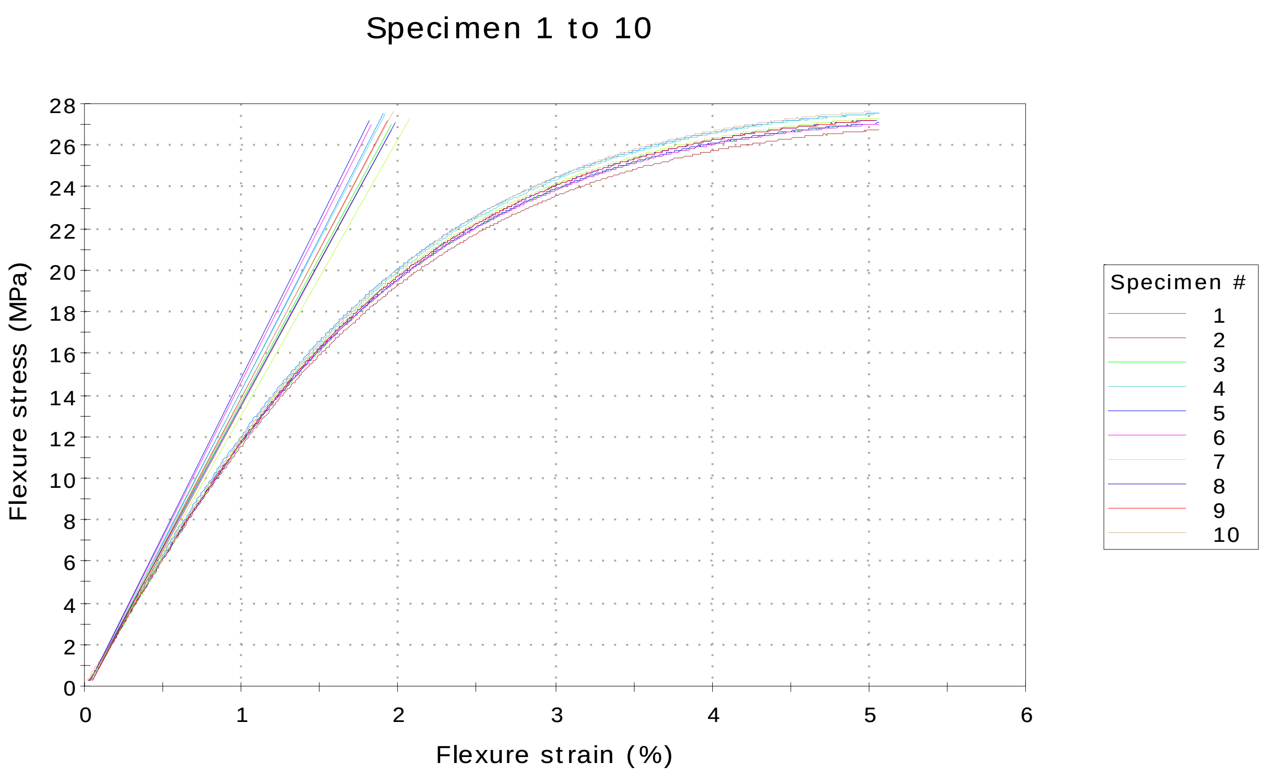
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	4.992	27.458	950.908	1191.547	1211.420
2	0.493	0.130	none	5.050	27.273	947.812	1183.295	1242.715
3	0.493	0.130	none	5.038	27.106	934.373	1178.936	1248.684
4	0.493	0.130	none	5.019	27.157	939.090	1163.295	1242.729
5	0.493	0.130	none	5.004	27.289	939.437	1189.488	1397.082
6	0.493	0.130	none	5.037	27.468	949.123	1172.823	1202.982
7	0.493	0.130	none	5.042	27.290	947.767	1183.255	1296.099
8	0.493	0.130	none	5.042	27.395	940.717	1206.487	1295.047
9	0.493	0.130	none	5.030	27.363	949.388	1186.866	1307.133
10	0.493	0.130	none	5.011	27.507	959.630	1181.724	1199.501
Maximum	0.493	0.130		5.050	27.507	959.630	1206.487	1397.082
Mean	0.493	0.130		5.026	27.331	945.825	1183.772	1264.339
Minimum	0.493	0.130		4.992	27.106	934.373	1163.295	1199.501
Standard Deviation	0.000	0.000		0.019	0.133	7.387	11.479	60.876

Ohio State University

ASTM D790 Procedure B

Material Type	50% Virgin 50% Painted Regrind

Graph 1



Results Table 1

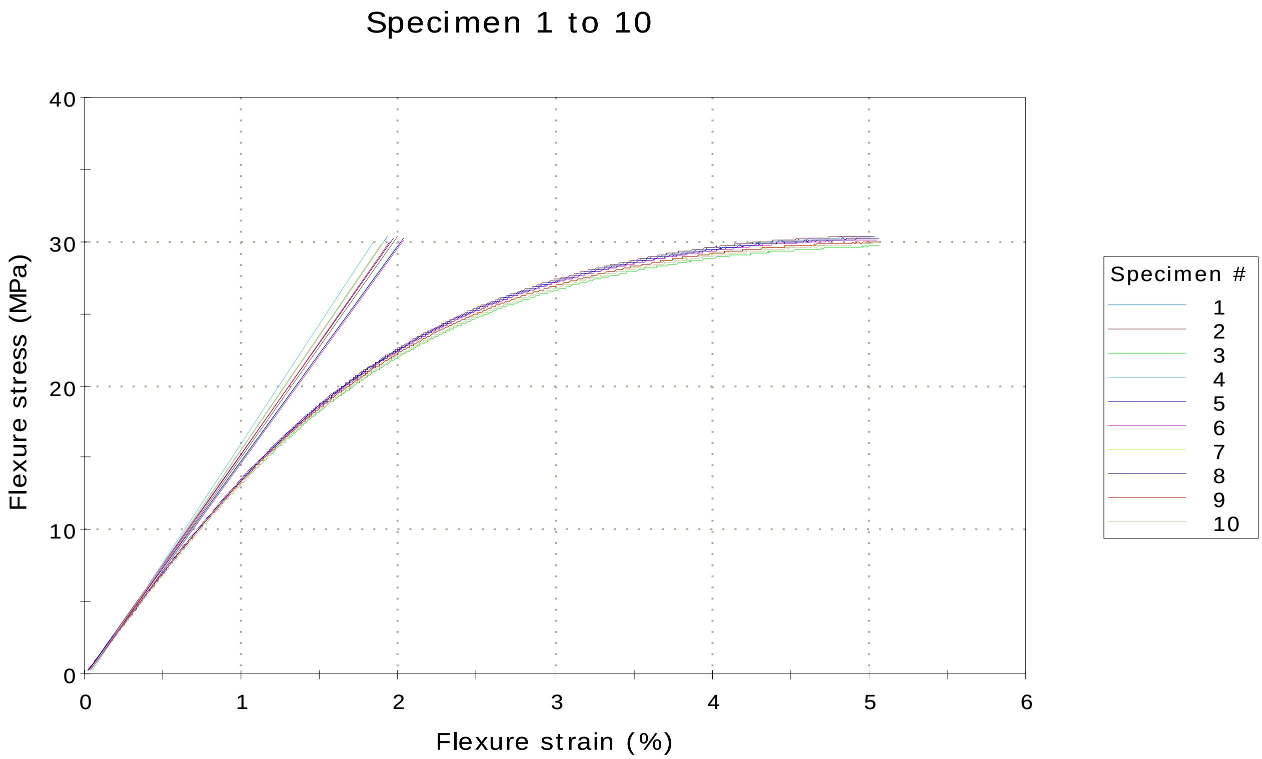
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.064	27.539	960.308	1263.610	1463.830
2	0.493	0.130	none	5.061	26.744	909.369	1210.950	1388.484
3	0.493	0.130	none	5.047	27.039	933.400	1225.882	1403.452
4	0.493	0.130	none	5.070	27.528	949.948	1245.586	1448.007
5	0.493	0.130	none	5.063	27.080	934.419	1222.761	1382.314
6	0.493	0.130	none	5.062	27.021	925.933	1231.436	1497.522
7	0.493	0.130	none	5.070	27.306	943.051	1239.536	1328.798
8	0.493	0.130	none	5.037	27.217	939.363	1230.326	1514.382
9	0.493	0.130	none	5.041	27.204	938.206	1230.563	1432.616
10	0.493	0.130	none	5.009	27.630	963.600	1222.178	1414.332
Maximum	0.493	0.130		5.070	27.630	963.600	1263.610	1514.382
Mean	0.493	0.130		5.052	27.231	939.760	1232.283	1427.374
Minimum	0.493	0.130		5.009	26.744	909.369	1210.950	1328.798
Standard Deviation	0.000	0.000		0.019	0.277	15.957	14.558	56.051

Ohio State University

ASTM D790 Procedure B

Material Type	20% Virgin 80% Unpainted Regrind

Graph 1



Results Table 1

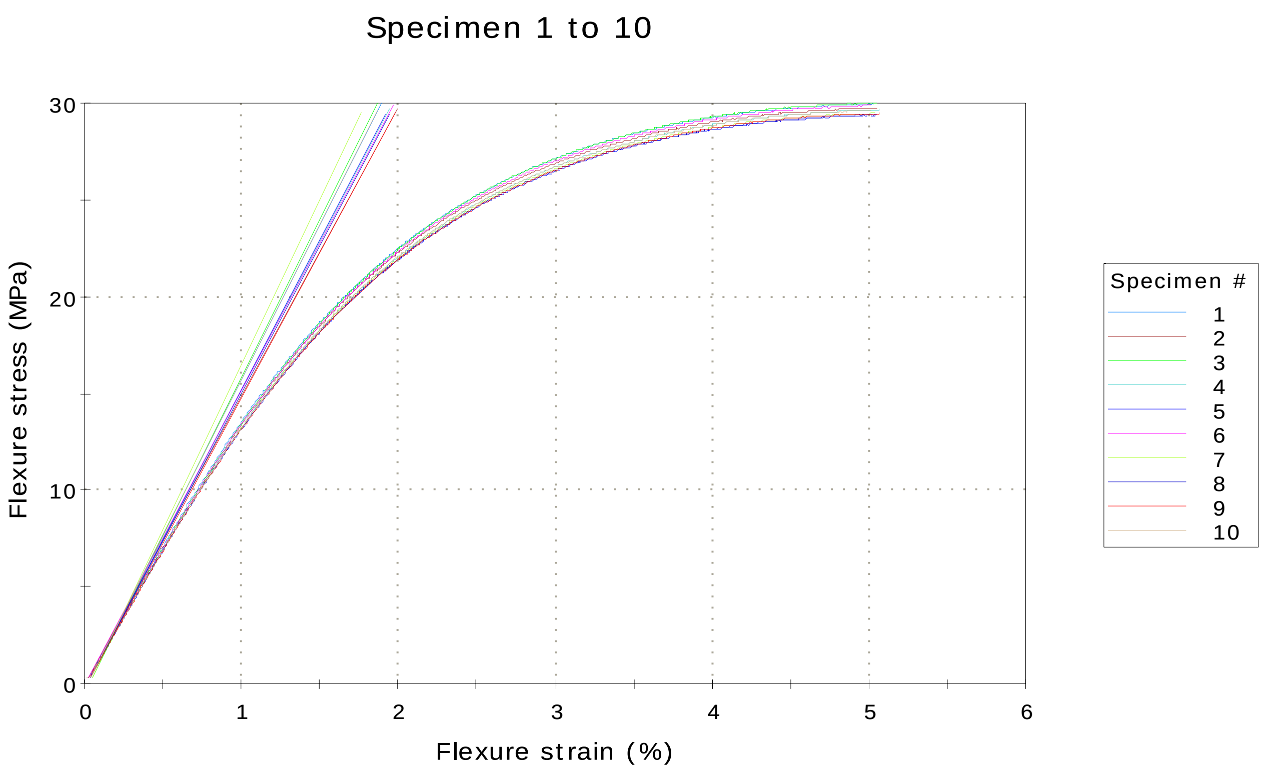
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.030	30.369	1131.188	1400.684	1595.585
2	0.493	0.130	none	5.025	30.406	1131.921	1405.190	1536.464
3	0.493	0.130	none	5.059	29.696	1087.867	1379.779	1507.177
4	0.493	0.130	none	5.043	29.930	1104.157	1391.647	1656.652
5	0.493	0.130	none	5.003	30.204	1121.353	1390.554	1500.011
6	0.493	0.130	none	5.044	30.142	1119.014	1386.942	1490.293
7	0.493	0.130	none	5.059	29.929	1113.513	1391.832	1589.353
8	0.493	0.130	none	5.060	30.235	1129.419	1397.592	1547.698
9	0.493	0.130	none	5.060	29.952	1107.262	1391.248	1556.997
10	0.493	0.130	none	5.009	29.828	1104.111	1369.547	1600.711
Maximum	0.493	0.130		5.060	30.406	1131.921	1405.190	1656.652
Mean	0.493	0.130		5.039	30.069	1114.981	1390.501	1558.094
Minimum	0.493	0.130		5.003	29.696	1087.867	1369.547	1490.293
Standard Deviation	0.000	0.000		0.022	0.237	14.326	10.220	52.760

Ohio State University

ASTM D790 Procedure B

Material Type	20% virgin 80% Painted Regrind

Graph 1



Results Table 1

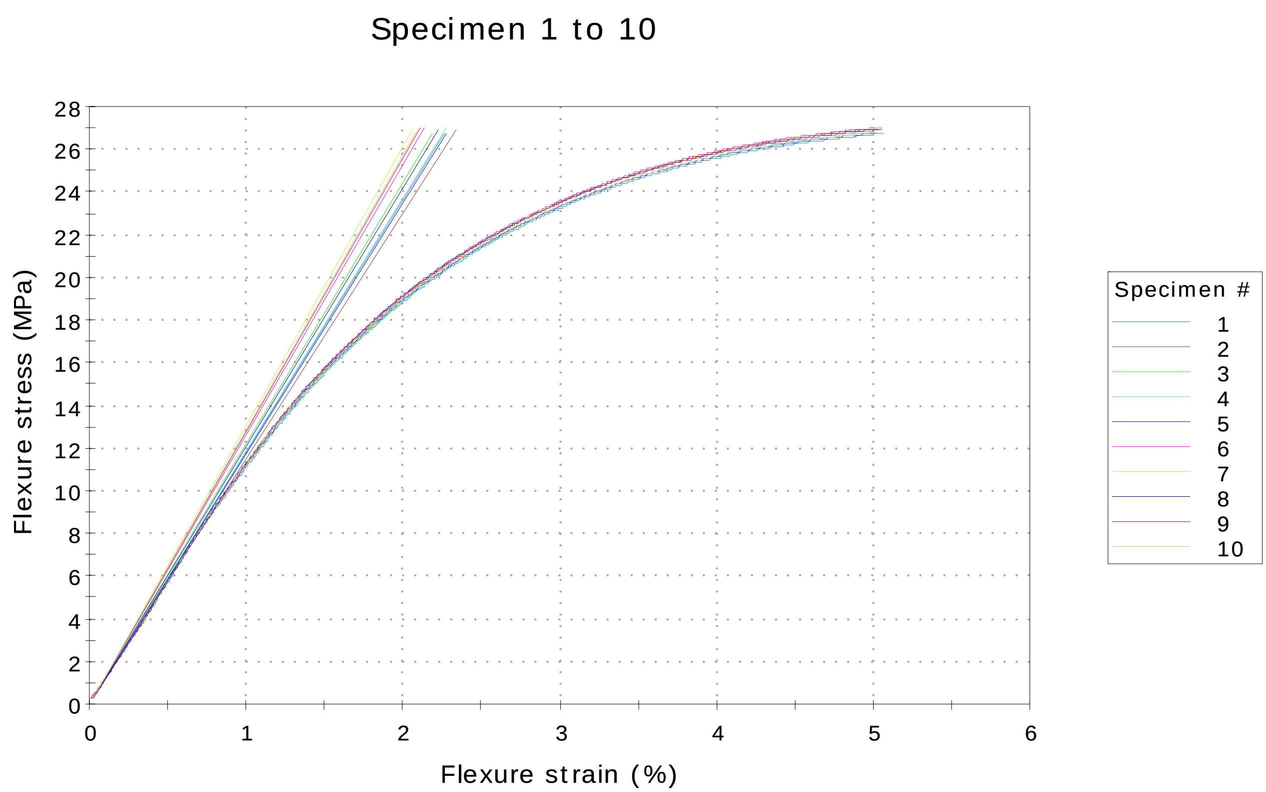
	Width (in)	Thicknes s (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.008	29.969	1124.162	1405.409	1603.186
2	0.493	0.130	none	5.012	29.745	1121.232	1389.683	1501.394
3	0.493	0.130	none	5.039	29.993	1127.171	1392.065	1633.314
4	0.493	0.130	none	5.071	29.664	1090.965	1377.722	1545.779
5	0.493	0.130	none	5.043	29.384	1086.592	1372.337	1552.461
6	0.493	0.130	none	5.019	29.878	1115.817	1387.381	1524.538
7	0.493	0.130	none	5.037	29.485	1096.184	1374.868	1701.207
8	0.493	0.130	none	5.024	29.415	1087.546	1367.896	1533.340
9	0.493	0.130	none	5.068	29.492	1082.826	1370.266	1499.758
10	0.493	0.130	none	4.984	29.640	1098.636	1369.798	1598.268
Maximum	0.493	0.130		5.071	29.993	1127.171	1405.409	1701.207
Mean	0.493	0.130		5.031	29.667	1103.113	1380.742	1569.325
Minimum	0.493	0.130		4.984	29.384	1082.826	1367.896	1499.758
Standard Deviation	0.000	0.000		0.027	0.225	17.172	12.335	64.175

Ohio State University

ASTM D790 Procedure B

Material Type	10% Virgin 90% Unpainted Regrind

Graph 1



Results Table 1

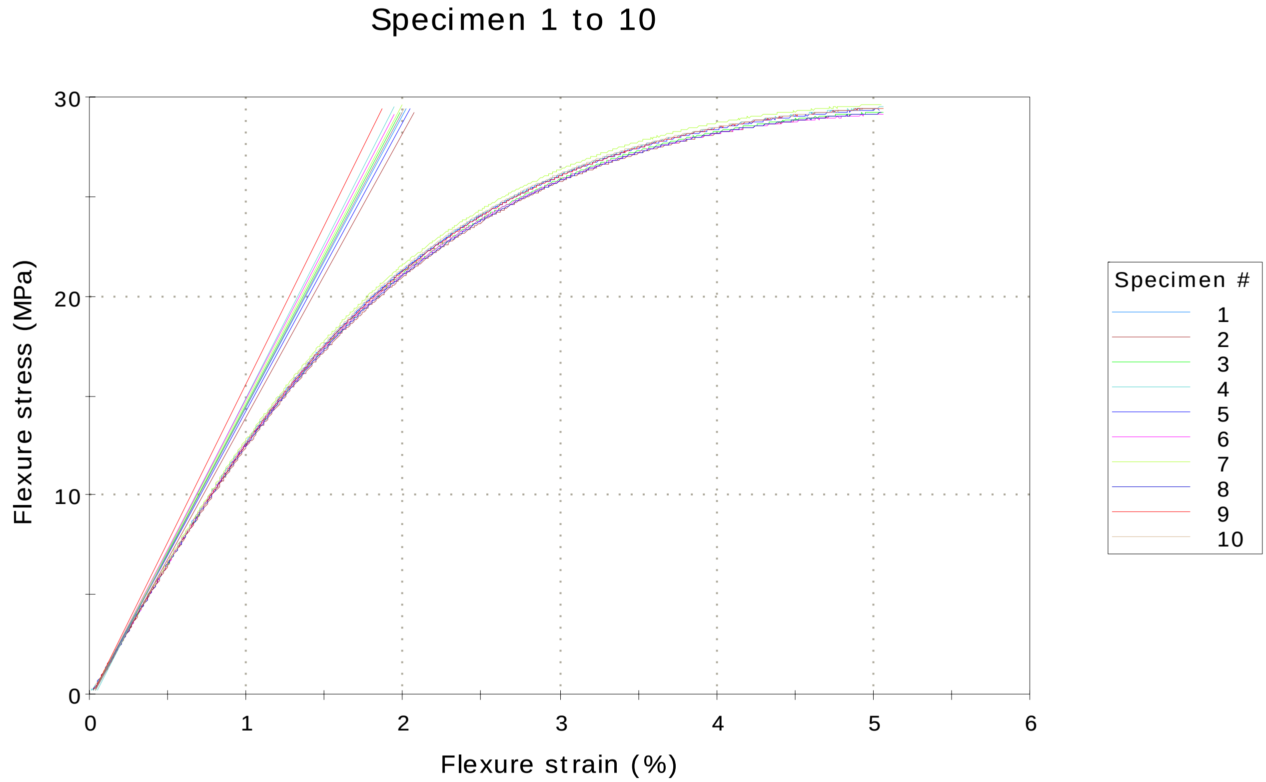
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.058	26.725	886.939	1124.514	1185.835
2	0.493	0.130	none	5.004	26.895	916.392	1141.878	1149.932
3	0.493	0.130	none	5.004	26.780	895.077	1137.923	1232.851
4	0.493	0.130	none	5.039	26.994	914.036	1155.026	1184.537
5	0.493	0.130	none	5.004	26.743	901.057	1148.242	1178.532
6	0.493	0.130	none	5.004	26.985	915.399	1159.042	1268.425
7	0.493	0.130	none	5.010	26.913	906.864	1158.580	1308.173
8	0.493	0.130	none	5.038	26.936	915.645	1151.033	1214.258
9	0.493	0.130	none	5.052	26.965	905.595	1140.480	1279.908
10	0.493	0.130	none	5.028	26.807	900.990	1150.789	1294.987
Maximum	0.493	0.130		5.058	26.994	916.392	1159.042	1308.173
Mean	0.493	0.130		5.024	26.874	905.799	1146.751	1229.744
Minimum	0.493	0.130		5.004	26.725	886.939	1124.514	1149.932
Standard Deviation	0.000	0.000		0.021	0.102	9.925	10.707	55.412

Ohio State University

ASTM D790 Procedure B

Material Type	100% Virgin

Graph 1



Results Table 1

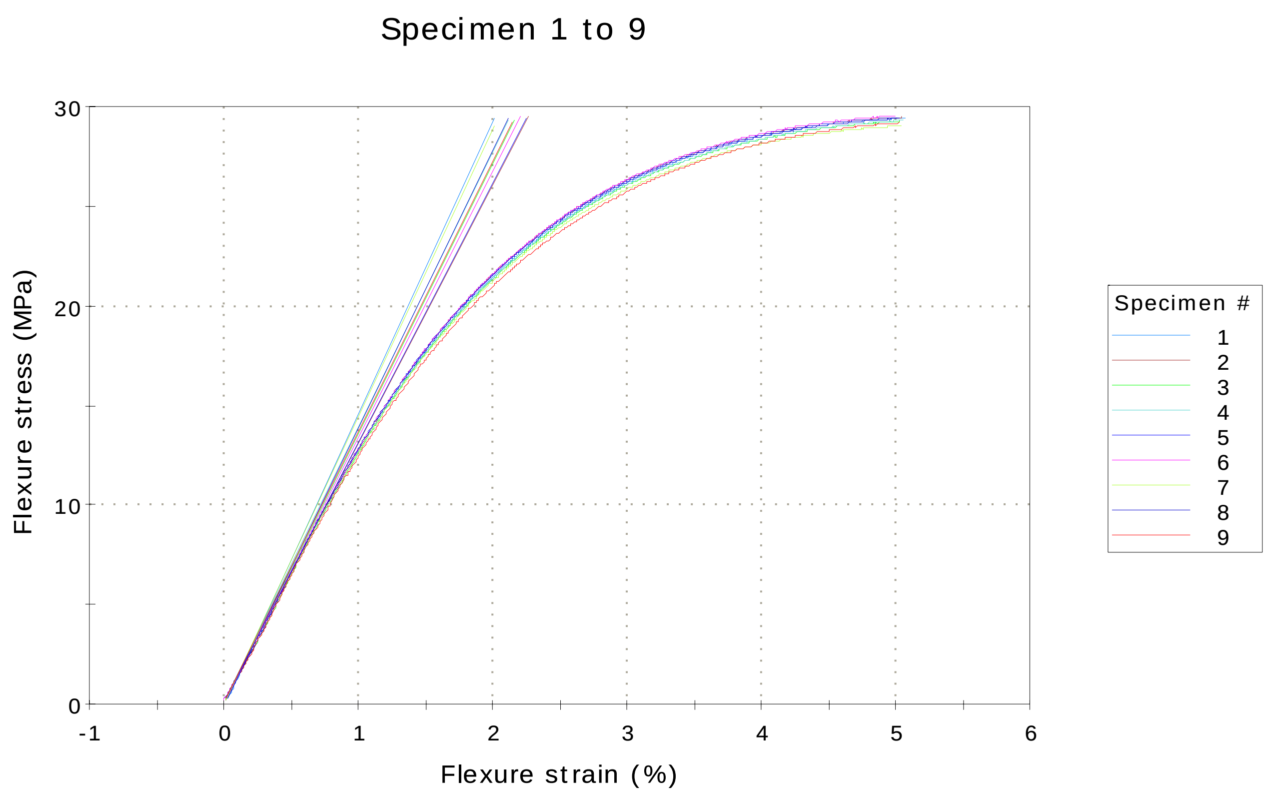
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.494	0.130	none	5.034	29.432	1029.000	1321.927	1474.904
2	0.494	0.130	none	5.051	29.202	1005.799	1295.558	1421.514
3	0.494	0.130	none	5.061	29.237	1018.261	1305.702	1496.264
4	0.494	0.130	none	5.055	29.493	1033.163	1307.295	1543.492
5	0.494	0.130	none	5.013	29.378	1036.375	1307.397	1449.930
6	0.494	0.130	none	5.035	29.153	1019.395	1311.681	1519.961
7	0.494	0.130	none	5.056	29.626	1050.983	1328.601	1502.660
8	0.494	0.130	none	5.053	29.211	1016.713	1301.700	1478.638
9	0.494	0.130	none	5.055	29.455	1033.664	1306.764	1600.630
10	0.494	0.130	none	5.053	29.432	1039.716	1314.467	1480.138
Maximum	0.494	0.130		5.061	29.626	1050.983	1328.601	1600.630
Mean	0.494	0.130		5.047	29.362	1028.307	1310.109	1496.813
Minimum	0.494	0.130		5.013	29.153	1005.799	1295.558	1421.514
Standard Deviation	0.000	0.000		0.015	0.154	13.265	9.612	49.982

Ohio State University

ASTM D790 Procedure B

Material Type	100% Unpainted Regrind

Graph 1



Results Table 1

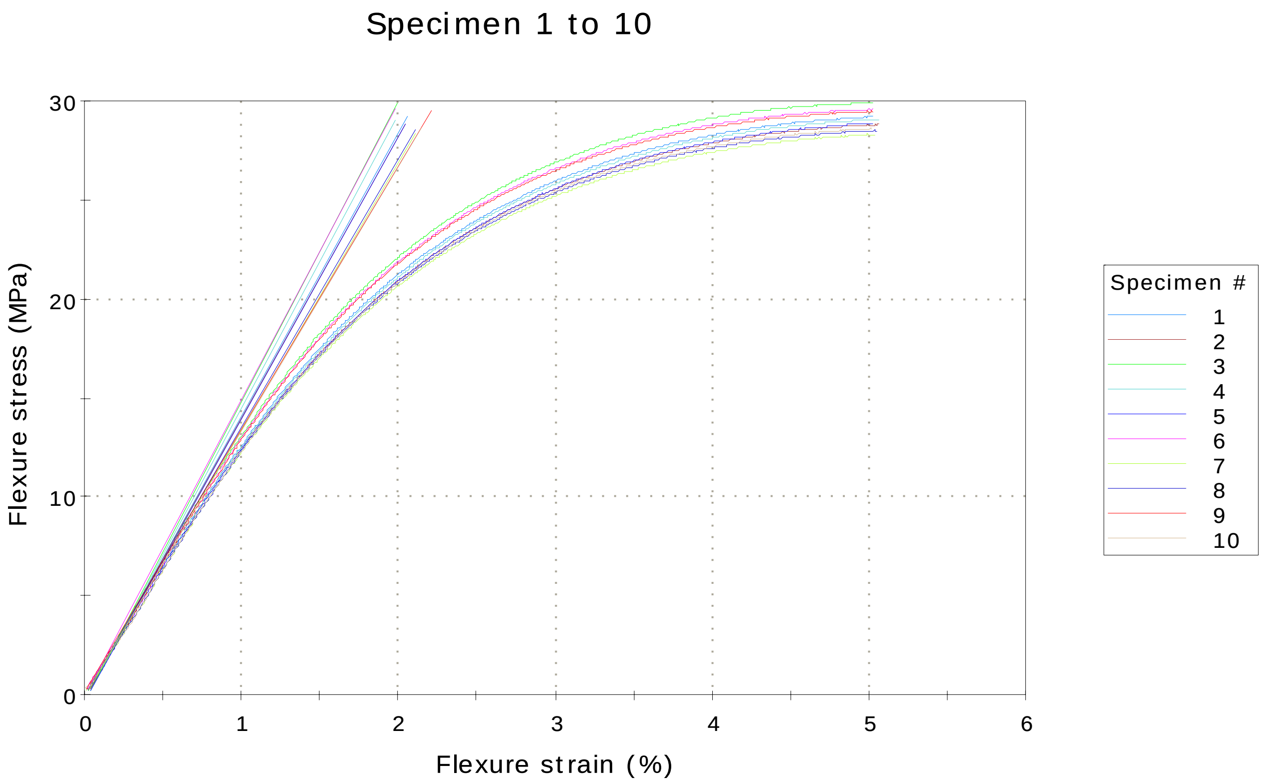
	Width (in)	Thickness (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.063	29.437	1044.753	1325.286	1473.098
2	0.493	0.130	none	5.050	29.483	1072.672	1288.491	1301.942
3	0.493	0.130	none	5.032	29.285	1058.301	1279.112	1356.927
4	0.493	0.130	none	5.059	29.327	1052.807	1290.098	1385.242
5	0.493	0.130	none	5.015	29.463	1070.649	1290.862	1306.239
6	0.493	0.130	none	5.000	29.549	1073.260	1293.741	1338.319
7	0.493	0.130	none	5.018	29.035	1039.733	1287.587	1438.499
8	0.493	0.130	none	5.010	29.404	1062.397	1307.433	1387.390
9	0.493	0.130	none	5.028	29.202	1024.465	1266.924	1362.372
Maximum	0.493	0.130		5.063	29.549	1073.260	1325.286	1473.098
Mean	0.493	0.130		5.031	29.354	1055.449	1292.170	1372.225
Minimum	0.493	0.130		5.000	29.035	1024.465	1266.924	1301.942
Standard Deviation	0.000	0.000		0.022	0.161	16.695	16.510	56.725

Ohio State University

ASTM D790 Procedure B

Material Type	100% Painted Regrind

Graph 1



Results Table 1

	Width (in)	Thicknes s (in)	Comments	Flexure strain at Maximum Flexure stress (%)	Maximum Flexure stress (MPa)	Modulus (E-modulus) (MPa)	Modulus (Secant) (MPa)	Modulus (Young's 0.01 % - 0.1 %) (MPa)
1	0.493	0.130	none	5.025	29.206	1039.593	1307.868	1431.418
2	0.493	0.130	none	5.060	28.807	1003.959	1300.752	1426.298
3	0.493	0.130	none	5.015	29.912	1096.945	1356.535	1507.206
4	0.493	0.130	none	5.068	29.074	1030.416	1296.683	1476.193
5	0.493	0.130	none	5.033	28.882	1012.472	1288.435	1423.346
6	0.493	0.130	none	5.024	29.591	1091.337	1302.428	1493.245
7	0.493	0.130	none	4.995	28.313	1008.006	1238.943	1345.477
8	0.493	0.130	none	5.038	28.516	1016.245	1245.509	1351.582
9	0.493	0.130	none	5.018	29.478	1086.096	1310.762	1335.310
10	0.493	0.130	none	5.010	28.606	1021.315	1240.976	1339.822
Maximum	0.493	0.130		5.068	29.912	1096.945	1356.535	1507.206
Mean	0.493	0.130		5.029	29.039	1040.639	1288.889	1412.990
Minimum	0.493	0.130		4.995	28.313	1003.959	1238.943	1335.310
Standard Deviation	0.000	0.000		0.022	0.511	36.644	37.226	66.377

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